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Dynamic and Static Exposure Tests and Evaluations of Alternative Copper-Based Antifoulant Coatings

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NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER RDT&E DIVISION
San Diego, California 92152–5001

K. E. EVANS, CAPT, USN
Commanding Officer

R. T. SHEARER
Executive Director

ADMINISTRATIVE INFORMATION

Work for this report was performed by members of the Environmental Chemistry/Biotechnology Branch, Code 521, in the Environmental Sciences Division at the Naval Command, Control and Ocean Surveillance Center RDT&E Division, San Diego, California, during the period of August 1988–July 1993.

Released by
J. G. Grovhoug, Head (Acting)
Environmental Chemistry/
Biotechnology Branch

Under authority of
P. F. Seligman, Head
Environmental Sciences
Division

EXECUTIVE SUMMARY

OBJECTIVE

Test and evaluate available commercial and experimental copper-based antifouling (AF) coatings for antifouling efficiency, paint deterioration, and copper leaching rate in dynamic/static cycling exposures that simulate ship activity. The results of the dynamic/static cyclic exposures were compared to those of simple static exposures.

RESULTS

Nine commercial and experimental paint systems were tested and evaluated for the 5 years between August 1988 and July 1993 in a dynamic/static cycle test. The F121 Navy standard paint, a non-ablative coating, served as control. Two other non-ablative coatings were included: M121, which is a modified F121 formula, and Devoe (D214). Devoe ABC3, a non-organotin version of Devoe ABC2, and International BRA540 were ablative Cu_2O coatings. Ameron 70 was also an ablative copper coating using copper flakes instead of the customary copper salts as biocide. Three paint systems (International SPC245, Devoe ABC2, and PETTIT) contained organotin and Cu_2O as biocides and served as additional reference paints for evaluation.

In the dynamic/static cycling exposure test, all AF coatings were effective in resisting biofouling throughout the length of their exposure. The paint systems ultimately failed, either because the paint integrity was weakened by blistering, peeling, and flaking, or because the AF coating was removed by erosion under the high currents.

The formula BRA540 performed best among the copper-based coatings; it had an effective lifetime of over 4 years that equals the performance of PETTIT and SPC245 organotin-based paint systems. Devoe F214 performed significantly better than the standard Navy F121 coating and proved to be effective for 6 years in the static exposure test. The ABC system appeared to be too soft, by ablating much faster than F121 or BRA540. Also, BRA540 performed better than ABC3 and F121 in the static exposure test. Ameron 70 had very poor paint integrity and caused severe galvanic corrosion where the bare steel was exposed by damage. Ameron 70 failed in both the static and the dynamic/static exposure tests.

Devoe 214 performed better than F121, but its paint erosion rate was higher than BRA540 in the dynamic/static cycle exposure test. In the static exposure, D214 showed practically no paint deterioration during the 6-year test, maintained its leaching rate at, or above, the critical 10 mg-Cu/cm^2/day level for 4 years, and only accumulated very moderate fouling. Devoe ABC3 eroded faster than F121 in the dynamic/static cycle exposure test and deteriorated faster than F121 in the static exposure. Ameron 70 was inferior to F121 in all tests. In addition, the metallic copper particles caused galvanic corrosion of the steel panel at locations where the bare steel became exposed under the damaged paint. The modified F121 formula, which contained 0.5% $(NH_4)_2SO_4$, did not show improved performance over the original formula, so the experiment was terminated.

PETTIT organotin paint served as the reference for performance. The other organotin paints, ABC2 and SPC254, deteriorated faster than PETTIT, so their exposure was also terminated before the full term of the experiment.

RECOMMENDATIONS

Select International BRA540 for the new Navy standard AF coating. It had the best overall performance in the static exposure and in the dynamic/static cycle exposure tests. In the dynamic/static test, it had the lowest paint deterioration/erosion rate and approached the performance of PETTIT, the best organotin/Cu_2O-based coating.

CONTENTS

FIGURES

TABLES

INTRODUCTION

OBJECTIVE

The objective was to test and evaluate the available commercial and experimental copper-based antifouling coatings for antifouling efficiency, paint deterioration, and copper leaching rates in alternating dynamic/static cycling exposures that simulate ship activity. The results of the dynamic/static cyclic exposures were compared to those of simple static exposures.

BACKGROUND

Ship hull protection from marine fouling organisms is essential for efficient fleet operation and energy conservation. Antifouling coatings contain some toxic material, such as organotin or copper, which is slowly released from the coating into the surrounding seawater, either by dissolution, hydrolysis, or diffusion. The released toxic material creates a toxic environment in the immediate vicinity of the coated surface and kills the attaching larval forms of the fouling organisms. In reality, toxic antifoulants, although ideally specific only to the target organisms, are toxic to nontarget organisms, and since toxics are being continually introduced into the environment, they may be an environmental hazard.

The Navy standard antifouling (AF) coatings F121 and F129 contain copper compounds as toxicants. The effective service life of the standard Navy AF coatings is approximately 2 years. Although these coatings have provided adequate protection against fouling organisms, AF coatings with an effective life of 5 years, or more, have now become a fleet requirement. In the last decade, very effective organotin-based AF coatings were developed for the commercial shipping industry. Organotin coatings may provide more than 5-year effective AF protection, but their high toxicity and persistence in seawater raised environmental concerns. Senate Resolution 272 banned the Navy from using the organotin AF paints. An alternative back-up system for organotin AF coatings is an extended-life Cu_2O-based coating.

Since it was believed that the failure of the Cu_2O-based coatings was caused by the green copper compounds that form a thick layer on the coating surface, underwater hull cleaning was developed to remove these deposits, and thereby, rejuvenate the leaching action of the unreacted copper oxide within the paint layers. It was found, however, that the benefit was short-lived because refouling occurred more rapidly after each cleaning. The brushed surfaces appear to form the green layer at an accelerated rate, partly because seeding crystals of the converted copper compound remained on the cleaned surface.

Test results indicated that the underwater removal of the green surface layers may not be adequate for extending the active service life of a Cu_2O-based AF coating, even when the thickness of the AF coating is increased to provide a reservoir of Cu_2O toxics. In FY 83, a cooperative project with DTNSRDC-2841 was initiated to study the rate of green layer formation on a few experimental and commercial formulations.

These studies revealed that the active red Cu_2O at the surface of the coating is converted to a very insoluble green compound with the formula of $CuCl_2 . 3Cu(OH)_2$, that may block the dissolution of the Cu_2O from the bulk of the coating. Based on these results, it appeared that if the green surface layer formation could be prevented, the effective service life of the

Cu_2O-based AF coating could be extended (Lindner, 1988). Since the formulation of the insoluble green compound is related to pH, measurements for surface color and surface pH were included in the early phases of the experiments. In an attempt to lower the surface pH, David Taylor Naval Ship Research and Development Center (DTNSRDC)* modified the F121 formula by adding $(NH_4)_2SO_4$. Other attempts to make surface pH less alkaline included using anticorrosion (AC) coatings, other than F150 epoxy, under the F121 AF paint.

TEST SUMMARY

Nine commercial and experimental paint systems were tested and evaluated for 5 years between August 1988 and July 1993. For the dynamic/static cycle test, the paint systems were applied to curved steel panels that fit the surface of a rotating drum immersed in San Diego bay. The drum was rotated at a peripheral velocity of 17 knots to simulate ship movement. One month of rotating the drum in dynamic cycle, was followed by 1 month of maintaining the drum stationary in the static cycle during first part of the test; the static cycle was then extended to 2 months. For the static test exposure, the antifoulant paint systems were applied to flat steel panels, then were immersed 3 feet below the seawater surface in San Diego bay.

The Navy standard paint F121, a non-ablative coating, was used as the control. Two other non-ablative coatings were included: M121, a modified F121 formula; and Devoe (D214). Devoe ABC3, a non-organotin version of Devoe ABC2, and International BRA540 were ablative Cu_2O coatings. Ameron 70 (AM70), an ablative copper coating using metallic copper flakes instead of the customary copper salts as biocide, was also tested. Three paint systems (International SPC245, Devoe ABC2, and PETTIT) contained organotin and Cu_2O as biocides and served as additional reference paints for evaluation. A preliminary static test included Farboil and Glidden paints that did not meet requirements; therefore, they were not evaluated in the dynamic/static cycling exposure tests.

TEST RESULTS SUMMARY

In the dynamic/static cycling exposure test, all AF coatings were effective in resisting biofouling throughout the length of their exposure. Any fouling, accumulated during the static phase, was usually removed by the 17-knot current during the dynamic phase. The paint systems ultimately failed, either because the paint integrity was weakened by blistering, peeling, and flaking, or because the AF coating was removed by erosion caused by the high circulating currents.

The BRA540 paint performed best among the copper-based coatings; it had an effective service lifetime of over 4 years that equaled the performance of PETTIT and SPC254 organotin-based paint systems. The Devoe 214 performed significantly better than the standard Navy F121 coating and proved to be effective for 6 years in the static exposure test. The ABC system appeared to be too soft and ablated much faster than F121 or BRA540. Also, BRA540 performed better than ABC3 and F121 in the static exposure test. Ameron 70 had very poor paint integrity and the metallic copper flakes caused severe galvanic corrosion wherever the bare steel was exposed to the seawater because of missing, flaked, or damaged paint. Ameron 70 failed in both the static and the dynamic/static exposure tests.

*DTNSRDC is now Carderock Division, Naval Surface Warfare Center.

TEST DESCRIPTION

TEST MATERIALS AND METHODS

Paint Systems Tested

On 18 April, eight packages, each containing 3- by 7-inch curved panels with the following listed identification codes, were received from DTNSRDC.

1. F 121
2. M 121
3. BRA 540–542–540
4. Devoe 214
5. ABC 3
6. ABC 2
7. PETTIT
8. 254–256–254 (International SPC 254)

In addition, four individual panels were received with the designations: 70–1, 70–2, 70–3, and 70–4. Table 1 lists the panels included in the dynamic and static cycling exposure test.

Table 1. List of tested paint panels.

Panel ID.*	Description	Color	No. Exp.
F121	Navy Standard AF	Dark Brown/Red	3
M121	F121 + .5% $(NH_4)_2SO_4$	Dark Brown/Red	3
BRA540	Ablative Cu_2O (International)	Glossy Brown/Red	4
D214	Non-Ablative Cu_2O (Devoe)	Red	3
ABC3	ABC–2 Without O-Tin (Devoe)	Glossy Medium Red	4
ABC2	O-Tin + Cu_2O (Devoe)	Glossy Dark Red	4
PETTIT	O-Tin + Cu_2O (PETTIT)	Blue/Green	3
SPC254	O-Tin + 30% Cu_2O (International)	Light Gray	4
AM70 (70–1, –2, –3, –4)	Metallic Cu Flakes (Ameron)	Red	4

*As referred to in following text and diagrams.

The paint systems containing organotin (ABC2, Pettit, and SPC254) were included as controls because the ultimate goal is to find a copper-based system that matches the efficiency of the organotin coatings.

We also received two batches of eight 10- by 12-inch, steel panels coated with ABC3 and BRA 540–542–540 for static exposure tests. These panels were exposed on 1 June 1988.

Devoe 214 and the ABC3 were tested also in a preliminary static exposure series that started on 1 June 1987. We report the results of the whole series that also included the following paint systems:

1. Glidden F-178-R-401R (G178)
2. Three Farboil paints:
   - Farboil C.R. 83023–15 (FBCR)
   - Farboil Super Tropical 1260 (FBST)
   - Farboil 844015–1 (FB84)
3. Two paint systems using AC paint other than F150:
   - Devoe 230 under F121
   - Devoe 234QC under F121

Exposure Test Methods

For static exposure, both sides of the flat, 10- by 12-inch, steel panels were coated with the selected experimental or commercial anticorrosion-antifouling coating systems. These coated panels were inserted in a vertical position into PVC frames (figure 1) suspended from a floating exposure platform and were immersed in San Diego bay 3 feet below the surface (figure 2).

The dynamic exposure apparatus consisted of an electric-motor-driven, 18-inch-diameter by 36-inch-long plastic drum immersed in seawater through the central well of the floating exposure platform (figure 3). The apparatus allowed for inspection and servicing because it could be raised and tilted into a near horizontal position. The outside of the 3- by 7-inch curved panels was coated with the selected experimental or commercial anticorrosion-antifouling coating systems. Because an AF coating on the inside of the unexposed side would have interfered with the leaching rate measurements, the inside of the panels was coated with epoxy only. The panels were attached to the surface of the drum and immersed into San Diego bay. The drum holds a total of 88 panels, with eight curved panels per row in 11 rows around the perimeter of the drum. The panels were attached to the drum in continuous rows to avoid cavitation erosion at the edges. Blank panels were used to fill incomplete rows. The drum rotation was adjusted to attain a peripheral velocity equivalent to 17 knots current to simulate the speed of a cruising ship. At the beginning, a 1-month dynamic (rotating) cycle was followed by 1-month static (stationary) cycle. After 39 months, the test protocol was changed to 2-months static and 1-month dynamic cycles to be consistent with the test protocol at other exposure stations.

Initially, the panels were tested after 1 day, 3 days, 1 week, 2 weeks, 4 weeks, and throughout the entire exposure period before and after the 1-month-long dynamic cycle. The tests included Leaching Rate (LR) by Atomic Absorption (AA) spectrometry; Fouling Rating (FR); Paint Deterioration Rating (PDR); surface color (% RED) by Tri-stimulus determination; and Surface pH (SpH). The surface conditions of the coatings were also recorded photographically. Because the manipulation of the tests interrupted the exposure continuum and the tested panels were dried for short periods of time, which could have adversely affected the paint integrity, only one of the exposed panels of each series was tested. The other panels underwent the exposure cycles without interruption and served as backups, in case the tested panels became deteriorated, damaged, or lost.

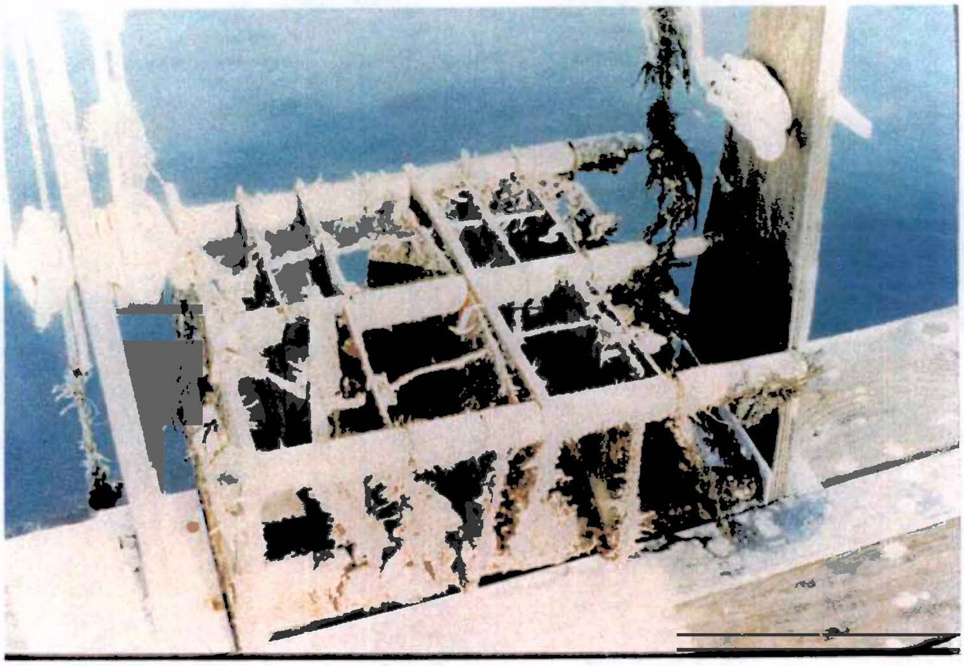


Figure 1. Plastic frame with slots to hold 10- by 12-inch panels for exposure.

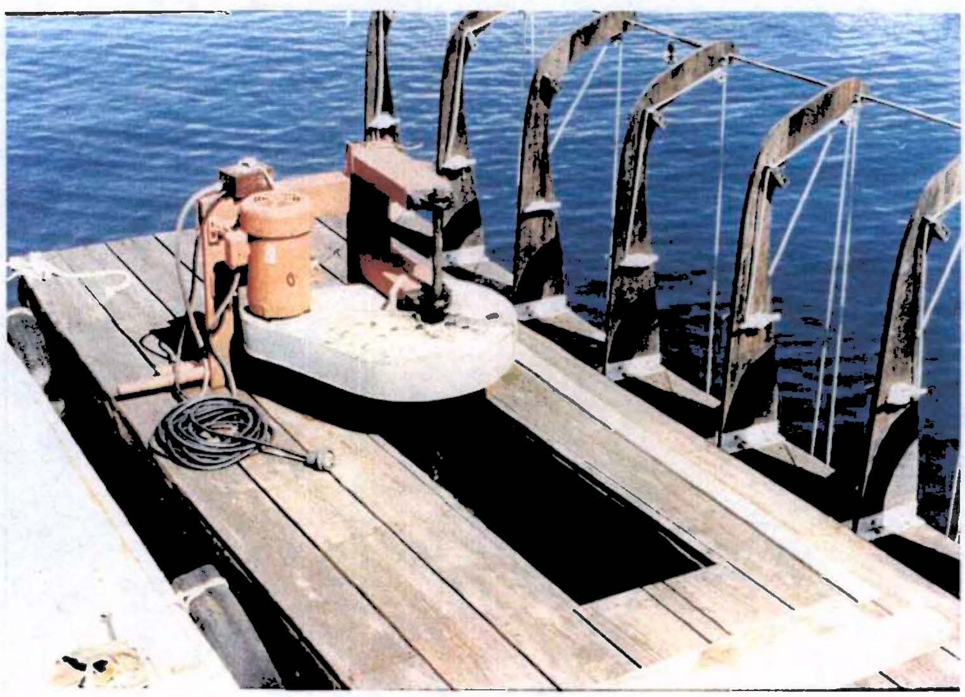


Figure 2. Exposure raft with support beams and pulleys to hang panel frames for immersion into seawater. The rotating drum for dynamic exposure is in the central well of the platform.

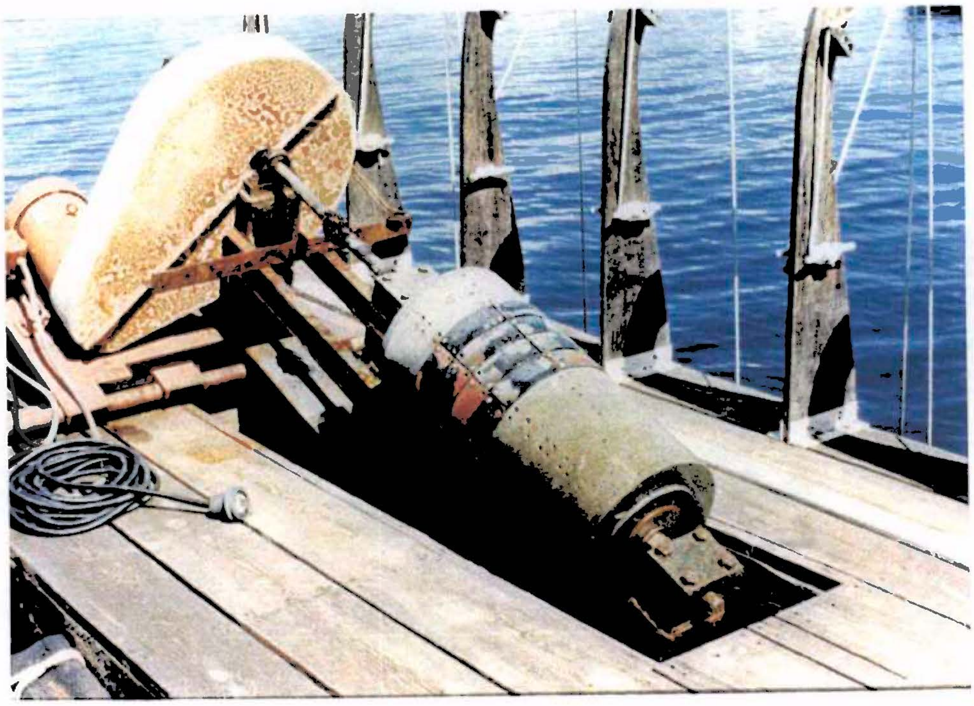


Figure 3. The dynamic exposure drum raised to servicing position.

Fouling Rating and Paint Deterioration Rating

The Fouling Ratings (FRs) and the Paint Deterioration Ratings (PDRs) were developed at DTNSRDC (DTNSRDC-83/091 report) and are listed in table 2.

Table 2. Fouling and paint deterioration ratings.

Rating	Fouling Rating (FR)	Paint Deterioration Rating (PDR)
10	incipient slime	AF paint intact
20	slime with dark patches	AF lost at edges
30	grass fouling	AF lost near edges
40	shells on edges	AF blisters + holes
50	shells 10 cm apart	ruptured blisters
60	shells 2 cm apart	AF/AC peeling
70	shells touching	AF/AC lost at edges
80	shells packed	rust under blisters
90	grass on shells	no AF/AC
100	tunicates on shells	steel pitted, rusty

This rating system was developed for ship hull evaluation and was used initially to evaluate the experimental paint systems. We soon learned, however, that the paint deterioration interfered with the objective evaluation of AF coating efficiency. A test panel may have appeared fouled, but often we found that under the fouled areas, the AF coating was missing either by eroding, flaking, or peeling off from the underlying surface. Because the primary objective of this program was to evaluate AF efficiency and since the overall performance of the total paint system was only secondary, we needed to separate the evaluation of fouling from that of paint deterioration. From photographic records, we re-evaluated and redefined the Fouling Rating (FR) as the

% area of the remaining AF coating (not necessarily the whole panel area) covered by the macrofouling organisms (defined as calcareous organisms and any other organisms with a thickness greater than 0.25 cm). Macrofouling on non-antifouling surfaces was ignored.

Similarly, the PDR is now reported as the % area of the panel covered by AF coating. Non-antifouling areas are identified by their color, texture, lack of antifouling properties, and from the number of remaining paint layers on the steel panel. A small cut or scratch on the paint with a scalpel helps to determine the number of paint layers.

Leaching Rate

Filtered seawater (10.3 L for each 10- by 12-inch panel, or 4.3 L for each curved panel) is placed into a 4- by 12- by 14-inch-high, polymethyl-methacrylate container then is allowed to reach equilibrium. After 1 hour, the test panel is attached to the agitating apparatus and immersed into the seawater. The agitating apparatus rotates a steel rod in an eccentric pattern at 60 rpm. The panel hanging from this rod oscillates through a 1-inch vertical distance at this rate in the seawater to provide gentle agitation that causes the water to pass in parallel with the panel surface. After 2, 4, and 6 hours, the seawater is gently stirred and approximately 3 mL is withdrawn with a syringe. The water sample is filtered through a 0.45-µm pore-size Millipore syringe filter and is acidified with nitric acid to 1% HNO_3 by volume. A 300-µL aliquot of acidified sample is diluted to 1 mL with 2% HNO_3 and standard addition spike. An amount equal to 10 µL of this mixture is autopipetted into a Graphite Furnace Atomic Absorption Spectrophotometer (Perkin Elmer, Model 5000). The copper content is analyzed under the following instrument program:

Dry:	10-s ramp to	120°C,	hold	50 s,	air	300 mL/min
Char:	50-s ramp to	720°C,	hold	20 s,	air	300 mL/min
Char:	10-s ramp to	1200°C,	hold	45 s,	air	300 mL/min
Cool:	1-s ramp to	20°C,	hold	20 s,	air	0 mL/min
Atom:	1-s ramp to	2100°C,	hold	7 s,	air	0 mL/min
Clean:	1-s ramp to	2600°C,	hold	3 s,	air	300 mL/min

s = seconds

Using a series of standard addition spikes, a calibration curve is obtained to calculate the concentration of copper. The leaching rate is calculated from the slope of the curve of copper content versus time.

Calculation:

$$\text{Leaching rate} = \frac{[\text{Cu}] \cdot \text{V} \cdot \text{HD}}{\text{A}} \qquad \mu\text{g Cu/cm}^2/\text{day}$$

where

[Cu]	=	slope of the leaching curve (Cu µg/mL/hr)
V	=	volume of seawater cm^3
HD	=	hours in one day (24)
A	=	paint area in cm^2

Originally, paint area A was calculated from the size of the panel,

where

$$A = 2\,(10 \times 12)\,2.54 \text{ in cm}^2 \text{ for the static panels,}$$

and

$$A = (3 \times 7)\,2.54 \text{ in cm}^2 \text{ for dynamic curved panels.}$$

Later, we found that some of the fouling accumulated on areas where the AF coating was missing, eroded or peeled away; therefore, these areas should be excluded from the calculations. In addition, those areas densely covered by heavy fouling are not exposed to the water and should also be excluded from the calculations. Based on the photographic records, the leaching rates were recalculated from the exposed AF coating area

(A = [Panel area] – [Eroded/Peeled-off area + Area covered by macro-foulers]).

Surface pH

The method for Surface pH (SpH) determination was developed during November and December 1986 by use of the following equipment and calibration method:

- Equipment: Corning pH/ion meter, Model 150, with Orion flat surface combination electrode #91–35.
- Calibration Method: The pH meter was calibrated by using pH 7.42 buffer for 1 hour. At 20°C, the pH is 7.43, the slope is 58.16.

The panel was placed on a horizontal surface and 10-mL synthetic seawater (3.1% NaCl solution) was spread over the surface by rolling a 0.5-inch PVC bar over the panel surface. The electrode was placed on a flat, smooth spot of the panel and allowed to touch the surface. The SpH was recorded after 45 minutes.

Surface Color Determination

Since in our previous experiments we found that the primary layer (slime) masked the surface color of the coating, this primary layer was removed by gentle wiping and washing the slime away before color determination. The color of the paint surface was then determined with a Reflection Meter, Photovolt Model 577, by using the Tri-stimulus method.

The Tri-stimulus method adopted by the International Commission of Illumination (I.C.I.) (Commission Internationale de l'Eclairage, C.I.E.) measures the reflectance of colored surfaces through three filters: amber, green, and blue. The reflection meter was standardized with each of these filters against a standard white surface. The measurements of the test surface, filtered through amber, green, and blue filters, gave the diffuse reflectance values Rx, Ry, and Rz, respectively. The Tri-stimulus values X, Y, and Z were derived from the diffuse reflectance values in the following equations:

$$X = 0.782\,Rx + 0.198\,Rz$$
$$Y = Ry$$
$$Z = 1.181\,Rz$$

For graphic representation on the chromaticity diagram, the chromaticity coordinates (x, y, and z) are derived from the tri-stimulus values by the following equations:

$$x = \frac{X}{X + Y + Z};\ y = \frac{Y}{X + Y + Z};\ z = \frac{Z}{X + Y + Z}$$

The x and y coordinates were plotted on the Maxwell triangle. The dominant wavelength (DWL) was obtained by drawing a straight line through the x and y plot of the sample and the achromaticity point C(x = 0.3100, y = 0.3162). The dominant wavelength was read at the intercept of this straight line and the perimeter of the Maxwell triangle. A computer program was developed to perform the dominant wavelength (DWL) calculation.

The % red was a more convenient value than DWL, and it was calculated by subtracting the DWL of the green color (550 nm) from the DWL of the sample (DWL – 550). This value represented the % red (DWL = 650; % Red = 650 – 550 = 100) remaining in the sample color.

X-Ray Fluorescence Spectrometry

The metallic components of the paint matrices were analyzed by using an Ortec Tube Excited X-ray Fluorescence Analyzer (TEFA). The surfaces of the painted panels were analyzed without further sample preparation.

TEST RESULTS

OVERALL EVALUATION

The dynamic/static exposure experiment started with the dynamic cycle on 28 July 1988. Because of the tests scheduled after 3, 7, 14, and 30 days of exposure, and also because of breakdowns, the first month's exposure was intermittent. Although the schedule was interrupted occasionally by breakdowns, maintenance activity, or relocation, the monthly dynamic cycle was followed as closely as possible. On 1 November 1991, the test schedule was changed to a 1-month dynamic cycle, followed by a 2-month static cycle to conform with the protocol at other exposure test stations. The starting dates of the static and dynamic cycles are detailed in table 3.

Since some of the panels lost most of the AF coating due to erosion and ablation, the dynamic exposure test for most of the series was discontinued after 950 days (32 months) of exposure. The panels were shipped back to DTNSRDC on 21 March 1991 for repainting.

The fouling rates, leaching rates, paint deterioration rates, surface pH and color were evaluated immediately before and after the dynamic cycle. Tables A-1 through A-3, in appendix A, contain the details of the fouling, leaching, and paint deterioration rates, respectively, for the full term of the experiment. Tables A-4 and A-5 of the appendix show the surface pH and color changes, respectively, during the first 6 months of the experiment. The surface pH and color measurements were discontinued after 6 months, because these tests were designed for the F121 type of AF paint and may not be applicable to the newer ablative paint systems.

In the appendices, tables A-1 through A-5 and graphs B-1 through B-5 may be used for comparison of the overall performance of the tested paint systems in the dynamic/static cycle exposure experiment. For a detailed analysis, the performance of each paint system will be evaluated individually and compared with that of the standard Navy F121. Table A-6 shows the details of the second dynamic exposure test on the Ameron 70 paint. Tables A-7 through A-11 contain the details of the static exposure experiments started on 1 June 1987, tables A-12 through A-16 for 1 June 1988, and table A-17 for 27 February 1989.

OVERALL DYNAMIC FOULING RATES

Table A-1 and graph B-1 show that most of the tested AF coatings provided protection against macro-fouling attachments for 4 years in the dynamic/static cycle exposure experiment. After a total exposure of 24 months, quite severe fouling appeared on the standard F121 and on the ABC2 panels during the 1-month static cycle in July 1990, which coincided with the heavy fouling season. Four marine tubeworms appeared on the edge of the D214 panel, but they were probably attached to the drum material, rather than the coating itself, and thus grew over the panel. During the dynamic cycle in August 1990, most of the marine tubeworms were washed away, and only the attachment site remained visible. During the next static cycle, the F121, M121, ABC3, and D214 accumulated some fouling that was washed away again in the following October dynamic cycle. Severe fouling appeared on F121 and D214, again in December 1991, and then again in July–October 1992. After 4-years of exposure, D214 remained fouled even after the dynamic cycles. BRA540 remained free of calcareous fouling for 40 months.

Table 3. Dynamic and static cycle start dates for exposure tests in schedule 1.

Dynamic Cycle (days)			Static Cycle (days)		
Start Date	**Duration**	**Total**	**Start Date**	**Duration**	**Total**
28 July 88	3	3	01 Aug 88	4	7
04 Aug 88	3	10	08 Aug 88	4	14
12 Aug 88	4	18	16 Aug 88	3	21
19 Aug 88	2	23	21 Aug 88	8	31
29 Aug 88	10	41	08 Sept 88	33	74
11 Oct 88	30	104	10 Nov 88	29	133
09 Dec 88	3	136	12 Dec 88	39	175
20 Jan 89	32	207	21 Feb 89	34	241
27 Mar 89	31	272	27 Apr 89	28	300
24 May 89	33	333	26 June 89	31	365
27 July 89	32	396	28 Aug 89	32	428
29 Sept 89	32	460	31 Oct 89	30	490
30 Nov 89	35	525	04 Jan 90	27	552
31 Jan 90	26	578	26 Feb 90	29	607
27 Mar 90	29	636	25 Apr 90	29	665
24 May 90	33	698	26 June 90	31	729
27 July 90	33	761	29 Aug 90	28	789
25 Sept 90	28	817	23 Oct 90	72	889
3 Jan 91	32	921	4 Feb 91	35	956
11 Mar 91	10	966	20 Mar 91 *	77	1043
6 June 91	32	1075	8 July 91	53	1128
30 Aug 91	30	1158	30 Sept 91 **	62	1220
5 Dec 91	35	1255	9 Jan 92	56	1311
5 Mar 92	36	1347	10 Apr 92	62	1409
11 June 92	33	1442	14 July 92	79	1521
1 Oct 92	35	1556	5 Nov 92	76	1632
20 Jan 93	33	1665	22 Feb 93	84	1749
17 May 93	37	1786	23 June 93	68	1854
30 Aug 93					

* The motor of the rotating drum failed, and a new motor had to be installed.

**On 01 Nov 91, the cycle system was changed to alternating 2-month static and 1-month dynamic periods to be consistent with the protocols of other exposure stations.

OVERALL DYNAMIC LEACHING RATES

The relatively good AF performance on the copper-based paints is the result of sufficiently high leaching rates that remained above, or near, the critical 10 μg-Cu/cm^2/day value for the entire 5 years of the experiment (table A-2 and graph B-2 of the appendix). The leaching rates of the copper-based coatings showed similar trends, starting at around 100 μg-Cu/cm^2/day and decreasing to a 20–30 μg-Cu/cm^2/day level within a couple of months. The leaching rates varied according to whether they were measured after a dynamic or a static cycle. In general, the leaching rates measured after the dynamic cycle were 10–20 μg-Cu/cm^2/day higher than those measured after the static cycle. The organotin-based paints (PETTIT, SPC254, and to a certain extent, ABC2) had lower Cu leaching rates that leveled off at about 10 μg-Cu/cm^2/day after a few months. The Cu leaching rates of these organotin-based paints showed less oscillation with the dynamic/static cycles than the Cu-based paints. After about 20-months of exposure, some of the leaching rates became erratic and exhibited occasional large spikes. This is related mainly to AF paint degradation (see table A-3 and graph B-3 in the appendices), and to a lesser extent, to fouling. (See table A-1 and graph B-1.) As detailed in the method section, the leaching rates were calculated from the exposed AF coating area ([Panel area] – [Eroded and Peeled-off area + Area covered by macro-foulers]). Calculations, based on a smaller AF area, when most of the AF coating eroded or peeled-off, magnified the experimental errors. Those areas with no AF coating left were usually heavily fouled, and the absorbed Cu on the heavy growth may have caused additional error.

OVERALL DYNAMIC PAINT DETERIORATION RATES

Fouling rate, and leaching rate evaluations apply to the AF coating surfaces only, and not necessarily, to the entire test panel surfaces. The failures of the paint systems were related to the eroding, flaking, and peeling of the AF coatings. Those test panel areas with missing AF coating usually accumulated heavy fouling, but were not counted in the fouling rate evaluation. Table A-3 and graph B-3 in the appendices indicate that erosion began exposing the bare AC coating under ABC3 as early as after a year of dynamic and static cycles. ABC2, F121, and the modified F121 (M121) began eroding after 18 months. Devoe 214 shows some deterioration after 18-months exposure, but serious loss of AF layer occurred only after 2-years exposure. BRA540 lost some AF layer after 24 months, but most of the paint remained intact for about 42 months, nearly equaling the performance of PETTIT and SPC254.

AF paint degradation appears to be affected by interruption of exposure to seawater; for example, both F121 and D214 panels, which were subjected to photography, leaching rate measurement, and other test interruptions that involved drying of the AF surface, lost their AF coating almost completely in about 30 months. To continue exposure tests in July 1991, these panels were replaced with backup panels that had undergone the same dynamic/static cycles. The backup panels, which had not been subjected to drying, still had about 50% of their AF coating.

Slime Layer Experiment

An experiment was initiated to determine whether or not the AF efficiency of an ablative Cu coating is adversely affected by a slime layer that dries on the surface during several weeks out of water. Some manufacturers claimed that the slime layer must be removed as soon as a ship gets into dry-dock to maintain efficiency of the AF coating.

On 1 February 1990, the surface of the ABC3-1, ABC3-2, BRA540-1, and BRA540-2 panels, which were exposed to static conditions in June 1989, were photographed and their leaching rates were measured. The slime was removed from panels ABC3-2 and BRA540-2 by gently rubbing them with paper towels under a constant stream of water. Removal of a small amount of red AF coating from ABC3-2 was observed. ABC3-1 and BRA540-1 panels were only rinsed with deionized water to remove the seawater, otherwise, the surfaces and the slime layer remained undisturbed. After allowing the panels to dry, each panel was identified with appropriate ID and date labels, then each was photographed on both sides.

Both sets of panels were placed on the roof of Building 111 (NRaD Marine Science and Technology laboratory building) and left to dry in ambient atmospheric conditions. The panels were positioned facing south at about a 45-degree angle, thus one side was exposed to sunshine and the other was in shade. At the selected location, the panels were never in shadows and were not protected from the elements.

After 1-week exposure, both panels with dried-on slime layer showed small, shallow cracks and flaking on the topside exposed to sunlight. The undersides of all panels were not affected.

After 3 weeks, the panels with the dried-on slime showed small cracks. In some places the dried slime layer curled up at the cracks, and the top paint layer adhered to the cracking slime, rather than to the underlying paint layers. This slime-induced flaking appeared to be more pronounced on the shady side. The cleaned panels did not show cracks.

After 4 weeks, the panels with slime layer showed cracking and peeling on both sides. The flakes on the topside were smaller in size than those on the underside. The two panels with slime layer removed showed no effects from exposure to air during the entire 8 weeks of the experiment.

After 8-weeks exposure, the ABC3-1 panel, on which slime layer was allowed to dry, showed flaking and cracking. The topside exposed to sunlight developed small flakes of approximately 1 by 1 mm and shallow cracks of 5 to 10 mm in length. On the underside of this panel, there were also some small flakes, but the cracks, more than 10 mm, were longer than those on the topside, were also deeper, and penetrated into several layers of AF coating.

The BRA540-1 with a dried slime layer was flaking over the entire panel surface. The flakes were approximately 1 by 1 mm and only included the surface AF layer. There were no visual differences between the side exposed to sunlight and the side in shade. No deep or long cracks were found.

After 60-days exposure to ambient atmospheric conditions, the panels were identified with appropriate ID and date labels, then they were photographed. On 3 April 1990, the panels were re-exposed to static seawater conditions. After the panels were returned to the ocean environment, the loose flakes were washed off, but no further losses of AF coating occurred. All panels accumulated slime at an equal rate.

After 30-days static exposure to seawater, the leaching rates of the panels from the slime experiments were measured on 7 and 8 May 1990. The leaching rates of the panels, with slime layer removed, decreased from 10 µg-Cu (ABC3) and 11 µg-Cu (BRA540) to 7 µg-Cu/cm^2/day. On the other hand, the leaching rates of those panels, which were dried with the slime layer on, increased from 11 to 13 µg-Cu/cm^2/day (ABC3) and from 10 to 11 µg-Cu/cm^2/day (BRA540). This increase in leaching rate may be the result of the cracks developed during exposure to air because the cracks increase the surface area, to expose the intact, not depleted, fresh AF surface. Two months later, in July, the cleaned ABC3 panel still showed a lower leaching rate than the one with the slime layer intact. Both the cleaned and uncleaned BRA540 panels had approximately the same leaching rates after 2 months.

OVERALL DYNAMIC COLOR RATES

Table A-4 and graph B-4 in the appendices clearly show that within a few weeks of exposure to seawater, F121 turned from red to green. In 6 months, the % red in the surface color of F121 reduced to zero. M121 is a F121 formula modified by addition of 0.5% $(NH_4)_2SO_4$ to increase the acidity (lower the pH) of the paint matrix. The lower pH should have prevented the formation of the green layer; however, our data indicate little, if any, improvement in maintaining the red AF layer by this method (figures 4 through 6). Devoe 214 showed slower green layer formation, but ABC2, ABC3, BRA540, and Ameron 70 remained red throughout the experiment. The original color of PETTIT and SPC254 were blue–green and light-green, respectively; therefore, their color was not monitored.

OVERALL DYNAMIC SURFACE pH

The initial surface pH of the tested paint systems varied from 7.76 (D214) to 9.15 (ABC3); the majority of the surface pH measurements were between 7.9 and 8.5 (table A-5 and graph B-5 in the appendices). With the exception of ABC3, the surface pH of most paint systems increased for 3 to 4 weeks, then decreased and leveled off between 7.9 and 8.4. The initial surface pH of the 0.5% $(NH_4)_2SO_4$ formula M121, a modified F121, was actually higher (8.08) than that of the unmodified formula F121 (7.91), but upon exposure, the pH of the modified formula was somewhat lower than that of the original F121. The pH of PETTIT and ABC2 appeared to be affected by the exposure cycles by increasing during the static and decreasing in the dynamic period. The final pH of the organotin-based coatings was lower (7.93 to 8.13) than that of the copper-based coatings. BRA540 had the lowest pH (8.18) among the copper paints.

DYNAMIC AND STATIC PERFORMANCE OF COPPER-BASED PAINT SYSTEMS

F121, Navy Standard AF Coating

The F121 AF coating began eroding after 18 months of dynamic/static cycle exposure. Those panels, which were subjected to photography, leaching rate, and other test interruptions involving the drying of the AF surface, almost completely lost their AF coating within 27 months (graphs B-6 and B-7). To continue the exposure tests in July 1991, these panels were replaced with backup panels that had undergone the same dynamic/static cycle, but were not tested. The backup panels that had never been dried still had about 50% of their AF coating.

The F121 provided good protection against fouling for 2 years. After which, the remaining AF coating fouled only during the heaviest fouling season in summer when in the static cycle. The currents generated in the following dynamic cycle removed the attached organisms.

The leaching rate dropped from over 100 μg-Cu/cm^2/day to about 25 μg-Cu/cm^2/day within 3 months. Although the red of the paint also turned green within 3 months, the change in color and leaching rate are probably not related because similar leach rate reduction occurred with paints that remained red. With few exceptions, we measured higher leaching rates after a dynamic cycle than after a static cycle. The water currents generated during the dynamic period apparently renewed the AF surface by removing some of the depleted layers, but they also caused erosion. Because of this AF surface renewal during the dynamic cycle, the average leaching rate remained above the critical 10 μg-Cu/cm^2/day to provide good AF effectiveness throughout the experiment. The leaching rate measurements became erratic after most of the AF coating was lost because of the large errors introduced into the calculation from a smaller area.

The paint integrity of F121 was preserved almost entirely during static exposure of 5 to 6 years (graphs B-8 through B-11 in the appendix). On the other hand, the leaching rate dropped below the critical 10 μg-Cu/cm^2/day within 3 to 4 months static exposure. The leaching rate increased temporarily during the warm summer months and showed a definite correlation between temperature and leaching rate. Under these circumstances, fouling protection was lost after 2 years in one experiment (graphs B-8 and B-9) and within 1 year in a previous experiment (graphs B-10 and B-11). The difference in AF efficiency between these two experiments may have been related to different batches of paints. F121 is formulated by a number of manufacturers and the military specification (MILSPEC) permits some variations; for example, the paint exposed in 1987 was bright cherry red and turned green much more slowly than the dark brownish/purple paint exposed in 1988 during the static and the dynamic/static tests. Also the surface pH of the 1987 batch increased much more slowly than that of the 1988 paint.

M121, Modified F121

The M121 paint is basically an F121 formula modified by addition of 0.5% $(NH_4)_2SO_4$ to increase the acidity (lower the pH) of the paint matrix and to prevent the formation of the green layer. The AF layer eroded quickly after 18 months dynamic/static exposure (graphs B-12 and B-13 in the appendix). The leaching rates of M121 and F121 were essentially identical. Similarly, the color changes of the original and the modified formula were identical as shown in figures 4 through 6 (and graph B-14 of the appendix). The surface pH of the 0.5% $(NH_4)_2SO_4$ modified formula was somewhat lower than that of the unmodified F121 (graph B-15 in the appendix), but no significant benefit from the 0.5% $(NH_4)_2SO_4$ addition was found. The exposure of the modified formula was discontinued after 32 months.

Devoe ABC3

The ABC3 is essentially the ABC2 organotin/Cu_2O-based ablative coating formula without the organotin component. ABC3 showed the fastest erosion among the tested paint systems in the dynamic/static exposure (graphs B-16 and B-17 in the appendix). Erosion could already be detected after only 6 months (figures 4 through 9) and complete loss of the AF layer appeared after only 15 months of exposure. Most of the AF was lost by the end of the second year (figures 8 and 9). The remaining AF paint showed reasonable protection against fouling. The leaching rate was strongly affected by the dynamic/static cycles, and it remained relatively high (avg 30 μg-Cu/cm^2/day). Apparently, ABC3 (and ABC2) are relatively soft formulations that cannot withstand high currents. Because of paint deterioration, the dynamic/static exposure of ABC3 was discontinued after 32 months.

Some deterioration of ABC3 was observed during static exposure, as well (graphs B-18 through B-19 in the appendix). In an earlier experiment, ABC3 started peeling off after only 6 months static exposure (graphs B-20 and B-21 in the appendix). The leaching rate of ABC3 in the static exposure was equivalent, or somewhat higher than that of F121. Also, it had slightly better AF efficiency than F121. The color of ABC3 varied throughout the 5-year exposure. By the end of the 6-month monitoring period, it had turned green (graph B-22 in the appendix). Later, it recovered its red and showed several cycles between red and green during the 5-year exposure. There was no significant difference between ABC3 and F121 in surface pH.

Figure 4. F121, M121 (modified F121), ABC3, and ABC2 before exposure.

Figure 5. After 10 days of dynamic exposure, F121 and M121 developed green layer on the surface. ABC3 and ABC2 remain red.

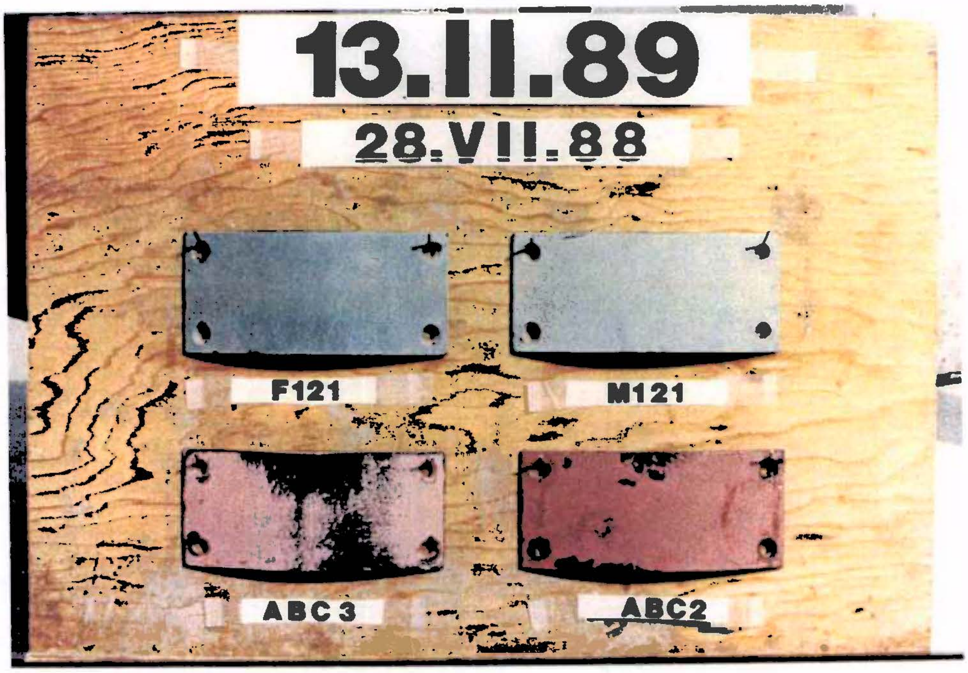


Figure 6. After 6 months of dynamic/static exposure, ABC3 and ABC2 show erosion.

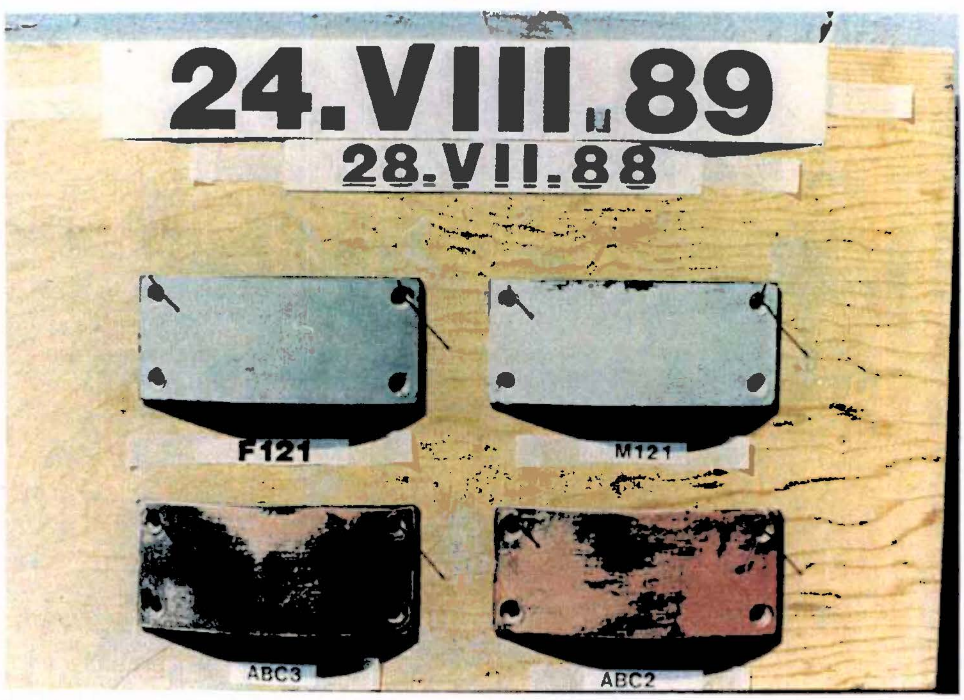


Figure 7. After 1 year of dynamic/static exposure, ABC3 completely lost one layer (red) of AF coating. ABC2 shows similar erosion. Loss of green AF coating appeared on the middle of the edge of M121.

Figure 8. After 2 years of dynamic/static exposure, ABC3 and ABC2 lost almost all of their AF coating. Most of F121 and M121 were also eroded. The bare areas accumulated fouling (tube-worms) during the static cycle.

Figure 9. The fouling was removed by the currents during the dynamic cycle, and the black areas that are without AF coating are clearly visible.

International BRA540

During dynamic/static cycle, gradual seawater erosion of the BRA540 paint began after 2 years of exposure; however, even after 5 years, approximately 40% of the AF paint was still functional (figures 10 and 11, graphs B-23 and B-24 in the appendix). The leaching rate remained above 20 μg-Cu/cm^2/day for approximately 3 years and remained above the critical 10 μg-Cu/cm^2/day throughout the 5-year test. Fouling occurred only after 4 years seawater immersion in the static cycle, and it was removed during the subsequent dynamic cycle.

No paint deterioration appeared throughout the 5-year static exposure test (graphs B-25 and B-26 in the appendix). The initially low (avg 25 μg-Cu/cm^2/day) leaching rate remained above the critical 10 μg-Cu/cm^2/day for 2 years, and stayed above 5 μg-Cu/cm^2/day for 5 years. Only minimal fouling (less than 5%) appeared after 3 years. BRA540 remained bright red throughout the entire 5-year test period. There was no significant difference between BRA540 and F121 in surface pH (graph B-27 in the appendix).

Devoe D214

The D214 is a non-ablative Cu_2O-based AF coating. It showed less erosion in the dynamic/static cycles than F-121 and started rapidly losing its AF coating only after 2 years (figures 10 and 11, graphs B-28 and B-29 in the appendix). Those panels which were subjected to photography, leaching rate, and other test interruption, that involved drying of the AF surface, almost completely lost their AF coating in about 30 months. To continue exposure tests, the depleted paint panels were replaced in July 1991 by backup panels that had undergone the same dynamic/static cycles. The backup panels had never been dried out and still had about 50% of their AF coating. D214 resisted fouling for approximately 30 months, but after that time, the backup panels fouled severely. The leaching rate of D214 remained above 20 μg-Cu/cm^2/day throughout the 5-year test.

In static exposure, D214 performed better than F121 (graphs B-30 and B-31 in the appendix). It showed practically no deterioration for 6 years and maintained the leaching rate above the critical 10 μg-Cu/cm^2/day level for over 3 years. Almost complete fouling protection was maintained for over 3 years, and the coating fouled more than 10% only occasionally for the total of 6 years of static exposure. D214 maintained its red longer than F121 (graph B-32 in the appendix), and its surface pH was approximately equivalent to that of F121.

Ameron 70

The dynamic exposure test of Ameron 70 was discontinued after the first month because about 50% to 100% of the top layer (AF) stripped off from all four panels (figures 12 and 13). This failure may have resulted from insufficient curing time before exposure to high currents. To allow for curing while stationary, a new set of panels was exposed at the beginning of the static cycle on 27 February 1989 (table A-6). For control, F121 was exposed at the same time. Simultaneously, two panels coated with Ameron 70 were exposed for static conditions (table A-17).

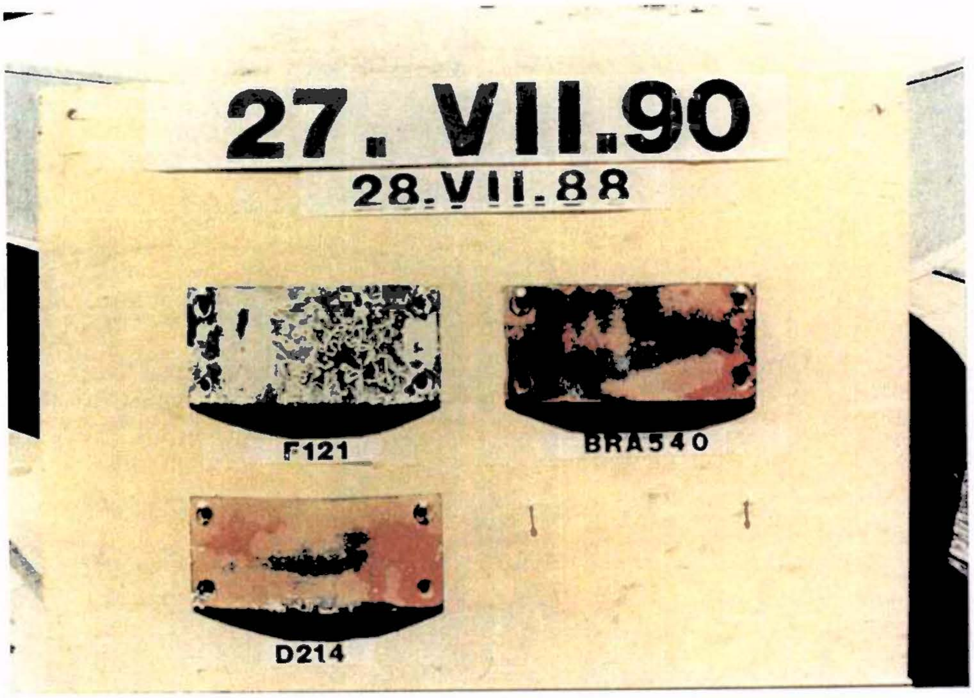


Figure 10. F121, BRA540, and D214 after 2 years of dynamic/static exposure. F121 accumulated fouling (tubeworms) during the static phase on surfaces where AF coating wore off. BRA540 and D214 are almost intact.

Figure 11. F121, BRA540, and D214 after 2 years of dynamic/static exposure at the end of the dynamic cycle. Fouling washed away from F121, the area (black AC F150) without AF coating is visible. Severe erosion of D214 appears. BRA540 is intact.

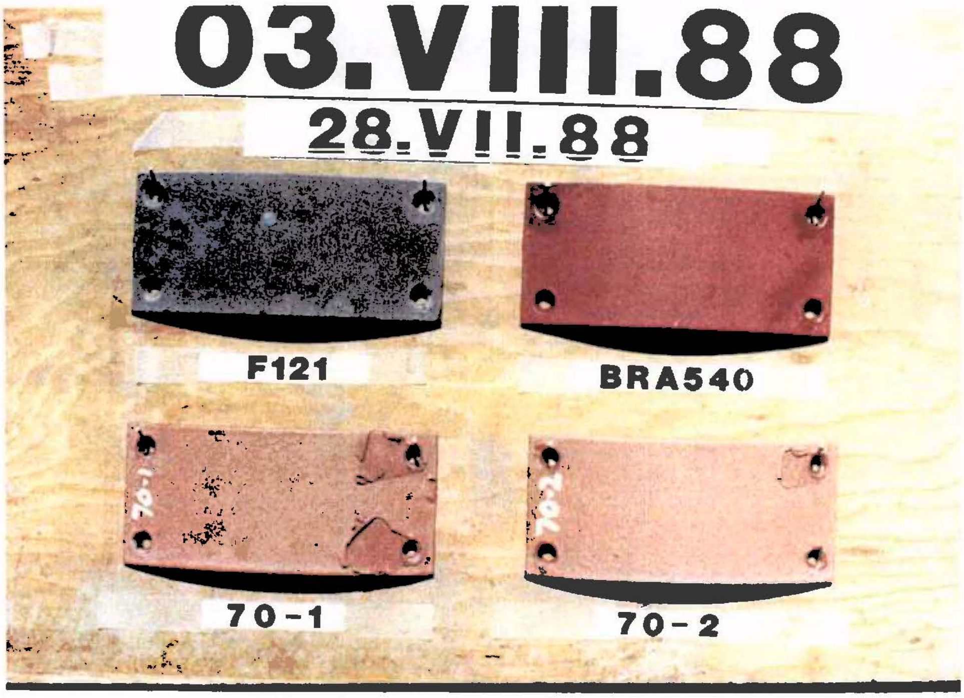


Figure 12. The top layer began peeling off at the corner holes of both Ameron 70 panels after only 4 days of dynamic exposure.

Figure 13. Most of the top layer of both Ameron 70 panels peeled off within 20 days of dynamic exposure.

After approximately 15 months of dynamic testing, the Ameron 70 panel, which was routinely tested for leaching rate, was lost during June 1990. Close examination of the other Ameron 70 panels on the drum of the dynamic exposure apparatus revealed that the paint eroded around the plastic fastening bolts. Since the Ameron 70 contains metallic copper flakes, galvanic cell action was created where the bare steel of the panel became exposed to seawater, and the severe corrosion enlarged the holes that accommodated the fastening bolts. Apparently, the holes became too large for the bolts so the panel was lost. This may be a serious fault of the Ameron 70 formulation containing metallic copper flakes. With this coating, a steel hull (if damaged or scraped) can corrode excessively. Tests should be designed to establish if cathodic protection can counteract the galvanic corrosion caused by metallic copper particles in the paint.

When Ameron 70 was exposed in the dynamic cycle, the initial high leaching rate of 104 $\mu g\text{-}Cu/cm^2/day$ increased within 3 weeks to 121 $\mu g\text{-}Cu/cm^2/day$, then plunged (more rapidly than that of the F121, graphs B-33 and B-34) to the near critical 10 $\mu g\text{-}Cu/cm^2/day$ level. When the exposure started in the static cycle, the initial low leaching rate again increased from 19 to 63 $\mu g\text{-}Cu/cm^2/day$, then dropped below the critical 10 $\mu g\text{-}Cu/cm^2/day$ level within 8 months.

A similar pattern was found in the static exposure (graphs B-35 and B-36). Here, the initial low leaching rate increased again from 9 to 53 $\mu g\text{-}Cu/cm^2/day$, then dropped below the critical 10 $\mu g\text{-}Cu/cm^2/day$ level within 8 months and fouled severely after 16 months.

DYNAMIC/STATIC PERFORMANCE OF ORGANOTIN-BASED PAINTS

Devoe ABC2

Devoe ABC2, an organotin Cu_2O-based ablative AF coating, served as performance comparison for the copper-based test paint system (graphs B-37 and B-38). As designed for ablation, ABC2 started rapidly eroding in the dynamic and static exposure test after 18 months, then lost almost all of its AF coating within 2 years. The leaching rate, affected by the currents generated by the rotation of the drum, showed large oscillations between the static and dynamic cycles. The fouling efficiency of ABC2 was comparable to F121 during the exposure test, which was terminated after 30 months.

PETTIT

The PETTIT, an organotin/Cu_2O-based ablative coating, performed the best among the tested paint systems and served as a performance standard (graphs B-39 and B-40). Serious erosion occurred only after 4 years dynamic/static cycles. Its Cu leaching rate remained above 10 $\mu g\text{-}Cu/cm^2/day$ for 30 months. After the 4 years, fouling appeared on PETTIT only during a static cycle, but it was removed by the currents during the next dynamic period.

International SPC254

The SPC254 was one of the more successful organotin/Cu_2O-based self-polishing (ablative) coating and was included in the test series for comparison (graphs B-41 and B-42). In the dynamic/static exposure it showed good fouling efficiency, but some erosion occurred after 20 months. Its Cu leaching rate dropped below 10 $\mu g\text{-}Cu/cm^2/day$ after 2 years and the test was discontinued after 30 months.

PERFORMANCE OF PAINT SYSTEMS IN STATIC EXPOSURE ONLY

This section details the performance of paint systems that were tested, starting 1 June 1987, in static exposure and were not tested further in dynamic/static exposure. In addition to F121 and D214, this series included

1. Glidden F-178-R-401R (G178),
2. Three Farboil paints:
   - Farboil C.R. 83023–15 (FBCR).
   - Farboil Super Tropical 1260 (FBST).
   - Farboil 844015–1 (FB84),
3. Two paint systems using AC paint other than F150:
   - Devoe 230 under F121.
   - Devoe 234QC under F121.

Information from the manufacturers indicated that the above formulations are principally copper-based coatings with no organotin contents; however, preliminary qualitative elemental analysis with X-Ray Fluorescence (XRF) Spectrometry revealed that Glidden F-178-R-401R contains little, if any, copper. Since presence of tin was detected, it may be an organotin-based antifouling formula. Other coatings contained either iron or zinc, or both, in various ratios as listed in table 4.

Table 4. XRF analysis of paints.

Paint System	Fe:	Cu:	Zn
D214	1 :	60 :	21
FBCR	1 :	10 :	2
FBST	1 :	6.2:	1.5
G178	20 :	0 :	1 (contains Sn)
FB84	1 :	34.5:	0

These results indicate that Zn and Fe additives are common in the commercial formulations. According to information from paint manufacturing companies, some additives, such as ZnO, were found to prevent the green layer formation. ZnO probably acted as cathodic protection for the Cu_2O to prevent its oxidation and dissolution.

Glidden F-178-R-401R (G178)

Since XRF analysis indicated that Glidden F-178-R-401R is probably an organotin-based paint without any copper content, its test was discontinued after 2-weeks exposure.

Farboil C.R. 83023–15 (FBCR)

FBCR began blistering and flaking almost immediately upon exposure to a marine environment. This deterioration continued gradually, and after 4-years exposure, 50% of the AF coating (graph B-43) was lost. The leaching rate was very erratic and probably was caused by flaking. After about 6 months, the leaching rate often dropped below the critical 10 µg-Cu/cm^2/day.

Some fouling had already accumulated with a few months exposure, but fouling remained moderate (below 10%) for 4 years. FBCR remained red during the entire 6-year test.

Farboil Super Tropical 1260 (FBST)

The FBST deteriorated rapidly by losing more than 50% of the AF coating within 18 months and 90% within 3 years (graph B-44). The Cu leaching rate of the AF coating dropped below the critical 10 µg-Cu/cm^2/day level within 6 months, and the coating failed against fouling. It retained its red color throughout the entire test period.

Farboil 844015–1 (FB84)

The FB84 retained its paint integrity better than any other paint system in this series. It also remained bright red during the entire test. The leaching rate, however, plunged below the critical 10 µg-Cu/cm^2/day level within 30 days, and the paint accumulated heavy fouling within 2 months (graph B-45 and figure 14).

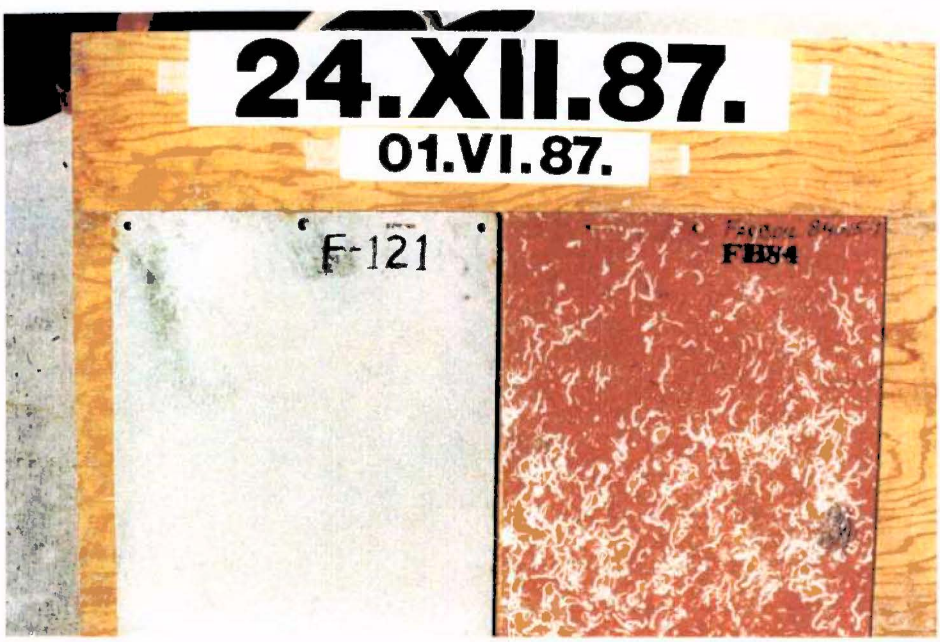


Figure 14. Farboil 844015–1 remained red, but accumulated heavy tubeworm growth within 6 months of static exposure.

Devoe 230 and 234QC under F121

This experiment's purpose was to explore the possibility of altering the surface pH, the red color retention, leaching rate, and other performance parameters of F121 by using anticorrosion coatings, other than the standard F150 epoxy coating, under the AF layer. Graph B-46 shows that the surface pH, with both D230 and D234QC, was higher than with F150. Previously, we showed that the higher, more alkaline pH favors the green layer formation (Lindner, 1988), and indeed, the color of F121, with D230 and D234QC, turned green faster than with F150 in the original system. The leaching rates with the experimental systems appeared to be somewhat higher than with F150, but the significance of these higher leaching rates was not evaluated. Because the experiment failed to achieve the intended goals of decreasing the surface pH and slowing down the color change from red to green, the exposure of these panels was terminated after 5 months.

CONCLUSIONS

International BRA540 had the best overall performance in the static and the dynamic/static cycle exposure tests. In the dynamic/static test, BRA540 had the lowest paint deterioration and erosion rate, and it approached the performance of PETTIT, the best organotin/Cu_2O-based coating. The leaching rate of BRA540 was maintained above the critical 10 µg-Cu/cm^2/day level and resisted fouling for 5 years. In the static exposure, BRA540 did not show deterioration and remained practically free of fouling for 5 years, even when the Cu leaching rate dropped slightly below the critical 10 µg-Cu/cm^2/day level after 2-years exposure.

Devoe 214 performed better than F121, but its paint erosion rate was higher than BRA540 in the dynamic/static cycle exposure test. In the static exposure, D214 maintained its leaching rate at, or above, the critical 10 µg-Cu/cm^2/day level for 4 years, accumulated only very moderate fouling, and showed practically no paint deterioration during the 6-year test.

Devoe ABC3 eroded faster than F121 in the dynamic/static cycle exposure test and deteriorated faster than F121 in the static exposure. The remaining ABC3 coating was equal to, or better than, F121 in leaching rate and fouling resistance.

Ameron 70 was inferior to F121 in all tests. In addition, the metallic copper particles caused galvanic corrosion of the steel panel wherever the bare steel became exposed under the damaged paint.

The modified F121 formula containing 0.5% $(NH_4)_2SO_4$ did not show improved performance over the original formula, so the experiment was terminated.

PETTIT organotin paint served as the reference for performance. The other organotin paints, ABC2 and SPC254, deteriorated faster; therefore, their exposure was terminated before the full term of the experiment.

With the exception of D214 and ABC3, the paint systems used in the 1987 static exposure series were inferior to F121; consequently, they were not included in the dynamic/static cycle test because they failed.

REFERENCE

Lindner, E. 1988. "Failure Mechanism of Copper Antifouling Coatings," *International Biodeterioration*, vol. 24, pp. 247–253.

APPENDIX A

TABLES

Table A-1. Fouling rate from 1 August 1988 to 24 August 1993.

Exp. (Days)	Test Date	*	Water Temp (°C)	Fouling Rate (% Macrofouling/AF Remaining)								
				F121	M121	BRA540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
4	01–Aug–88	S		0	0	0	0	0	0	0	0	0
11	08–Aug–88	S		0	0	0	0	0	0	0	0	0
21	18–Aug–88	S		0	0	0	0	0	0	0	0	0
40	06–Sept–88	S		0	0	0	0	0	0	0	0	0
70	06–Oct–88	D		0	0	0	0	0	0	0	0	0
103	08–Nov–88	S		0	0	0	0	0	0	0	0	0
132	07–Dec–88	D		0	0	0	0	0	0	0	0	0
175	19–Jan–89	S		0	0	0	0	0	0	0	0	0
208	21–Feb–89	D		0	0	0	0	0	0	0	0	0
238	23–Mar–89	S		0	0	0	0	0	0	0	0	0
270	24–Apr–89	D		0	0	0	0	0		0	0	0
298	22–May–89	S		0	0	0	0	0		0	0	0
333	26–June–89	D		0	0	0	0	0		0	0	0
362	25–July–89	S		0	0	0	0	0		0	0	0
396	28–Aug–89	D		0	0	0	0	0		0	0	0
425	26–Sept–89	S		0	0	0	0	0		0	0	0
459	30–Oct–89	D		0	0	0	0	0		0	0	0
489	29–Nov–89	S		0	0	0	0	0		0	0	0
523	02–Jan–90	D		0	0	0	0	0		0	0	0
550	29–Jan–90	S		0	0	0	0	0		0	0	0
578	26–Feb–90	D		0	0	0	0	0		0	0	0
607	27–Mar–90	S		0	0	0	0	0		0	0	0
636	25–Apr–90	D		0	0	0	0	0		0	0	0
664	23–May–90	S	21	0	0	0	0	0		0	0	0
698	26–June–90	D	23	0	0	0	0	0		0	0	0
726	24–July–90	S	22	16	0	0	0	2		32	0	0
761	28–Aug–90	D	22	0	0	0	0	0		0	0	0
789	25–Sept–90	S	22	4	3	0	10	3		0	0	0
817	23–Oct–90	D	21	0	0	0	0	0		0	0	0
852	27–Nov–90	S	18	0	0	0	0	0		0	0	0
889	03–Jan–91	D	17	0	0	0	0	0		0	0	0
921	04–Feb–91	S	20	0	0	0	0	0		0	0	0
950	05–Mar–91	D	20	0	8	0	0	0		0	0	0
1042	05–June–91	S	19	0		0		0			0	
1076	09–July–91	D	21	**		0		**			0	
1128	30–Aug–91	S	22	5		0		8			0	
1160	01–Oct–91	D	22	0		0		0			0	
1225	05–Dec–91	S	19	22		4		15			0	
1260	09–Jan–92	D	19	0		0		0			0	
1316	05–Mar–92	S	20	0		0		0			0	
1352	10–Apr–92	D	20	0		5		0			0	
1414	11–June–92	S	22	0		9		10			0	
1450	17–July–92	D	22	25		5		0			0	
1526	01–Oct–92	S	22	100		N/D		100			34	
1561	05–Nov–92	D	20	0		29		81			0	
1624	07–Jan–93	S	21	0		5		71			0	
1670	22–Feb–93	D	17	0		0		30			0	
1740	03–May–93	S	21	0		0		0				
1792	24–June–93	D	22	0		0		0				
1853	24–Aug–93	S	22	2		23		1				

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.

Table A-2. Leaching rate from 1 August 1988 to 24 August 1993.

Exp. (Days)	Test Date	*	Water Temp (°C)	Leaching Rate (μg–Cu/cm^2/day) F121	M121	BRA540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
4	01–Aug–88	S		167	164	92	191	102	104	94	90	64
11	08–Aug–88	S		147	136	78	141	88	112	75	73	58
21	18–Aug–88	S		107	102	70	107	71	129	62	58	39
40	06–Sept–88	S		84	46	40	48	62	33	48	42	30
70	06–Oct–88	D		37	40	41	50	35	27	32	23	16
103	08–Nov–88	S		39	37	42	54	29	19	39	21	13
132	07–Dec–88	D		26	34	28	47	34	15	17	14	13
175	19–Jan–89	S		31	32	27	33	17	12	23	9	10
208	21–Feb–89	D		28	31	46	54	50		43	17	13
238	23–Mar–89	S		27	25	30	39	23		15	9	8
270	24–Apr–89	D		49	49	52	49	53		53	13	13
298	22–May–89	S		35	35	37	36	18		14	18	14
333	26–June–89	D		35	43	38	40	51		41	17	16
362	25–July–89	S		38	36	16	22	25		17	14	8
396	28–Aug–89	D		25	24	33	36	31		30	20	17
425	26–Sept–89	S		25	24	22	11	24		19	12	9
459	30–Oct–89	D		36	32	32	70	35		40	23	14
489	29–Nov–89	S		25	23	26	41	24		21	8	9
523	02–Jan–90	D		30	24	37	56	41		33	25	12
550	29–Jan–90	S		20	17	22	25	24		21	12	10
578	26–Feb–90	D		51	92	44	106	49		44	29	20
607	27–Mar–90	S		8	26	17	49	20		28	20	11
636	25–Apr–90	D		26	43	31	36	27		43	20	20
664	23–May–90	S	21	15	26	18	22	20		23	11	11
698	26–June–90	D	23	17	35	32	45	14		46	20	11
726	24–July–90	S	22	21	56	29	50	18		32	14	13
761	28–Aug–90	D	22	13	47	25	9	27		39	25	11
789	25–Sept–90	S	22	3	33	25	41	19		16	9	9
817	23–Oct–90	D	21	35	46	27	25	59		24	11	7
852	27–Nov–90	S	18	32	63	17	N/A	27		N/A	7	5
889	03–Jan–91	D	17	18	38	16	N/A	24		N/A	10	6
921	04–Feb–91	S	20	46	97	25	N/A	32		N/A	11	8
950	05–Mar–91	D	20	12	43	17	8	22		31	9	7
1042	05–June–91	S	19	N/A		N/A		N/A			N/A	
1076	09–July–91	D	21	**		N/A		**			N/A	
1128	30–Aug–91	S	22	27		19		25			5	
1160	01–Oct–91	D	22	14		10		24			7	
1225	05–Dec–91	S	19	15		5		9			4	
1260	09–Jan–92	D	19	86		25		51			17	
1316	05–Mar–92	S	20	21		10		11			6	
1352	10–Apr–92	D	20	26		13		23			10	
1414	11–June–92	S	22	38		16		15			5	
1450	17–July–92	D	22	24		13		9			5	
1526	01–Oct–92	S	22	N/D		53		N/D			1	
1561	05–Nov–92	D	20	34		25		37			13	
1624	07–Jan–93	S	21	42		13		50			6	
1670	22–Feb–93	D	17	20		9		19			9	
1740	03–May–93	S	21	100		19		68				
1792	24–June–93	D	22	50		12		11				
1853	24–Aug–93	S	22			15						

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.

Table A-3. Paint deterioration rate from 1 August 1988 to 24 August 1993.

Exp. (Days)	Test Date	*	Water Temp (°C)	PDR (% AF Remaining/Original Panel Area) F121	M121	BRA540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
4	01–Aug–88	S		100	100	100	100	100	100	100	100	100
11	08–Aug–88	S		100	100	100	100	100	100	100	100	100
21	18–Aug–88	S		100	100	100	100	100	100	100	100	100
40	06–Sept–88	S		100	100	100	100	100	100	100	100	100
70	06–Oct–88	D		100	100	100	100	100	100	100	100	100
103	08–Nov–88	S		100	100	100	100	100	100	100	100	100
132	07–Dec–88	D		100	100	100	100	100	100	100	100	100
175	19–Jan–89	S		100	100	100	100	100	100	100	100	100
208	21–Feb–89	D		100	100	100	100	100	100	100	100	100
238	23–Mar–89	S		100	100	100	100	100	100	100	100	100
270	24–Apr–89	D		100	100	100	100	100		100	100	100
298	22–May–89	S		100	100	100	100	100		100	100	100
333	26–June–89	D		100	100	100	100	100		100	100	100
362	25–July–89	S		100	100	100	100	100		100	100	100
396	28–Aug–89	D		100	100	100	99	100		100	100	100
425	26–Sept–89	S		100	100	100	98	100		100	100	100
459	30–Oct–89	D		100	100	100	71	100		100	100	100
489	29–Nov–89	S		100	100	100	66	100		100	100	100
523	02–Jan–90	D		96	100	100	69	100		100	100	100
550	29–Jan–90	S		95	100	100	52	100		100	100	100
578	26–Feb–90	D		61	48	100	32	98		67	100	100
607	27–Mar–90	S		64	46	100	29	97		63	100	100
636	25–Apr–90	D		43	42	100	25	94		58	100	100
664	23–May–90	S	21	45	42	100	27	94		34	100	100
698	26–June–90	D	23	48	41	100	13	86		23	100	92
726	24–July–90	S	22	42	37	100	14	89		27	100	92
761	28–Aug–90	D	22	45	34	97	22	59		15	100	92
789	25–Sept–90	S	22	23	29	97	9	60		15	100	92
817	23–Oct–90	D	21	6	32	92	11	21		12	100	92
852	27–Nov–90	S	18	6	32	92	10	21		12	100	92
889	03–Jan–91	D	17	5	30	93	5	31		20	100	92
921	04–Feb–91	S	20	5	30	93	5	31		11	100	92
950	05–Mar–91	D	20	5	23	93	5	25		9	100	91
1042	05–June–91	S	19	5		93		25			100	
1076	09–July–91	D	21	**35		81		**46			100	
1128	30–Aug–91	S	22	36		81		48			100	
1160	01–Oct–91	D	22	36		83		46			100	
1225	05–Dec–91	S	19	29		80		31			100	
1260	09–Jan–92	D	19	17		68		26			94	

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.

(Contd)

Table A-3. Paint deterioration rate from 1 August 1988 to 24 August 1993 (continued).

Exp. (Days)	Test Date	*	Water Temp (°C)	PDR (% AF Remaining/Original Panel Area)								
				F121	M121	BRA540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
1316	05–Mar–92	S	20	22		63		28			92	
1352	10–Apr–92	D	20	20		63		22			88	
1414	11–June–92	S	22	12		67		16			86	
1450	17–July–92	D	22	12		62		18			84	
1526	01–Oct–92	S	22	N/D		N/D		N/D			68	
1561	05–Nov–92	D	20	6		59		22			35	
1624	07–Jan–93	S	21	6		51		13			37	
1670	22–Feb–93	D	17	5		49		8			29	
1740	03–May–93	S	21	3		36		2				
1792	24–June–93	D	22	2		40		5				
1853	24–Aug–93	S	22	2		23		1				

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.
**The original test panel was taken off the drum to accommodate the new S/D series. Alternate F121 and D214 panels with more AF coating remaining are being tested from this point.

Table A-4. Surface color from 1 August 1988 to 19 January 1989.

Exp. (Days)	Test Date	*	Surface Color (% Red Remaining in Sample)								
			F121	M121	BRA 540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
4	01–Aug–88	S	40	81	62	89		52	67		
11	08–Aug–88	S	53	49	65	70	55	52	93		
21	18–Aug–88	S	18	31	64	71	52	56			
40	06–Sept–88	S	21		60	64	52	47			
70	06–Oct–88	D	21	21	52	55	50	46	60		
103	08–Nov–88	S	12	21	47	64	55	37	60		
132	07–Dec–88	D	7	19	52	61	49	49	60		
175	19–Jan–89	S	0	6	52	59	29	49	65		

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.

Table A-5. Surface pH from 1 August 1988 to 19 January 1989.

Exp. (Days)	Test Date	*	Surface pH								
			F121	M121	BRA 540	ABC3	D214	AM70	ABC2	PETTIT	SPC 254
4	01–Aug–88	S	7.91	8.08	8.00	9.15	7.76	8.51	7.89	8.37	8.21
11	08–Aug–88	S	8.36	8.20	8.28	8.45	7.87	8.60	8.49	8.34	9.29
21	18–Aug–88	S	8.67	8.38	8.41	8.24	8.17	8.69	8.48	8.48	8.30
40	06–Sept–88	S	8.48	8.31	8.38	8.08	8.38	8.50	8.42	8.56	8.42
70	06–Oct–88	D	8.22	8.14	8.15	8.09	8.09	8.01	7.87	7.80	7.85
103	08–Nov–88	S	8.15	8.06	8.17	8.14	8.13	7.85	8.15	8.27	7.90
132	07–Dec–88	D	8.20	8.16	8.12	8.14	8.12	7.90	7.99	7.94	7.97
175	19–Jan–89	S	8.31	8.36	8.18	8.27	8.30	8.13	8.13	8.05	7.93

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.

Table A-6. Ameron 70.
1 March 1989 to 5 March 1991 dynamic/static exposure test series

Exp. (Days)	Test Date	*	Water Temp (°C)	Fouling Rate (% Remaining)		Leaching Rate (μg-Cu/Cm²/day)		PDR (% Covered by AF)	
				F121	AM70	F121	AM70	F121	AM70
3	1–Mar–89	S		0	0	179	19	100	100
7	6–Mar–89	S		0	0	133	42	100	100
14	13–Mar–89	S		0	0	88	59	100	100
28	27–Mar–89	S		0	0	71	63	100	100
58	26–Apr–89	D		0	0	52	46	100	100
86	24–May–89	S		0	0	32	27	100	100
121	28–June–89	D		0	0	42	31	100	100
150	27–July–89	S		0	0	31	21	100	100
184	28–Aug–89	D		0	0	44	25	100	100
213	28–Sept–89	S		0	0	22	12	100	100
246	31–Oct–89	D		0	0	44	7	100	100
276	29–Nov–89	S		0	0	26	6	100	100
311	02–Jan–90	D		0	0	44	9	100	100
338	29–Jan–90	S		0	0	24	13	100	100
366	26–Feb–90	D		0	0	60	30	100	100
395	27–Mar–90	S		0	0	17	13	100	100
424	25–Apr–90	D		0	0	26	9	100	100
452	23–May–90	S	21	0	0	15	3	100	100
486	26–June–90	D	24	0	**	20	**	100	XX
514	24–July–90	S	22	50	45	17	13	100	100
549	28–Aug–90	D	22	0	5	9	5	100	95
577	25–Sept–90	S	22	40	30	8	5	100	95
605	23–Oct–90	D	21	0	5	13	3	100	95
640	27–Nov–90	S	19	40	30		3	100	95
676	03–Jan–91	D	19	40	50	8	3	100	95
708	04–Feb–91	S	20	0	0		2	100	90
736	05–Mar–91	D	20	0	0	7	1	100	90

*Column identifies Exposure (Exp.) test period: (D) signifies Dynamic and (S) denotes Static testing.
**Panel lost: (holes corroded), alternate panel is evaluated.

AF = Fouling Rate. The % remaining AF Coating covered by fouling. Leaching Rate (in μg-Cu/Cm²/day), where
[A = (Panel Area) – (Eroded/Peeled-off Area + Area covered by macro-foulers)]
PDR = Paint Deterioration Rate. The % Area of the panel covered by AF Coating.

Table A-7. Fouling rate.
1 June 1987 to 10 August 1993 exposure test series

Exp. (Days)	Test Date	Water Temp (°C)	Fouling Rate (% Macrofouling/AF Remaining)					
			F121	ABC3	D214	FBCR	FBST	FB84
1	02–June–87		0	0	0	0	0	0
8	09–June–87		0	0	0	0	0	0
15	16–June–87		0	0	0	0	0	10
30	01–July–87		0	0	0	0	0	20
63	03–Aug–87		0	0	0	0	0	30
94	03–Sept–87		10	0	0	0	10	30
128	07–Oct–87		10	0	0	10	10	40
204	22–Dec–87		10	10	0	10	10	40
268	24–Feb–88		10	10	10	10	10	40
325	21–Apr–88		10	10	10	20	20	50
387	22–June–88		20	20	10	20	20	50
448	22–Aug–88		40	30	10	30	40	60
505	18–Oct–88		40	30	20	30	40	60
570	22–Dec–88		50	30	10	30	50	70
638	28–Feb–89		50	30	10	30	50	70
696	27–Apr–89		30	20	10	20	50	50
749	19–June–89		50	20	10	20	60	60
812	21–Aug–89	20	60	20	10	20	70	70
876	24–Oct–89	20	60	30	10	20	80	80
933	20–Dec–89		60	40	10	20	85	80
1011	08–Mar–90		60	50	10	25	85	85
1074	10–May–90	21	60	70	10	20	80	80
1124	29–June–90	N/A	60	70	10	20	80	80
1137	12–July–90	25	60	70	10	25	80	80
1155	30–July–90	N/A	60	70	10	25	80	80
1186	30–Aug–90	N/A	60	70	10	25	80	80
1217	30–Sept–90	N/A	60	70	10	30	80	80
1256	08–Nov–90	18	60	70	15	30	80	80
1317	08–Jan–91	17	75		10	30		
1466	06–June–91	20	70		20	50		
1690	16–Jan–92	17	80		20	70		
1864	08–July–92	21	90		4	25		
2068	28–Jan–93	19	68		13	75		
2262	10–Aug–93	21	82		12	97		

Exp. = Exposure time in days.
AF = Antifoulant painted surface.

Table A-8. Leaching rate.
1 June 1987 to 10 August 1993 exposure test series

Exp. (Days)	Test Date	Water Temp (°C)	Leaching Rate (μg-Cu/cm²/day)								
			F121	ABC3	D214	D230	D234	FBCR	FBST	FB84	G178
1	02–June–87		75	36	49	55	81	58	30	51	5
8	09–June–87		69	34	74	78	61	39	49	23	5
15	16–June–87		70	33	36	51	54	36	27	17	4
30	01–July–87		23	17	14	17	21	15	14	5	
63	03–Aug–87		13	19	19	13	22	12	14	10	
94	03–Sept–87		14	15	17	21	14	32	16		
128	07–Oct–87		12	22	26	24	18	41	29	10	
204	22–Dec–87		8	7	7			10	5	3	
268	24–Feb–88		10	5	8			7	4	3	
325	21–Apr–88		3	4	6			1	0	1	
387	22–June–88		10	11	16			14	5	4	
448	22–Aug–88		8	4	13			13	4	2	
505	18–Oct–88		5	36	10			14	4	4	
570	22–Dec–88		3	0	10			7	1	1	
638	28–Feb–89		2	6	9			6	1	1	
696	27–Apr–89		7	18	15			22	6		
749	19–June–89		5	14	13			16			
812	21–Aug–89	20	39	19	27			56			
876	24–Oct–89	20	14	15	7			18			
933	20–Dec–89		2	9	8			6			
1011	08–Mar–90		7	7	10			11			
1074	10–May–90	21	1	0	8			5			
1137	12–July–90	25	15	0	13			23			
1201	14–Sept–90	23	0	0	4			10			
1256	08–Nov–90	18	4		5			4			
1317	08–Jan–91	17	1		2			5			
1466	06–June–91	20	5		6			11			
1690	16–Jan–92	17	6		3			15			
1864	08–July–92	21			17			106			
2068	28–Jan–93	19	23		3			83			
2262	10–Aug–93	21	15		5			30			

Exp. = Exposure time in days.
Leaching Rate (in μg-Cu/Cm2/day) where
[A = (Panel Area) – (Eroded/Peeled-off Area + Area covered by macro-foulers)]

Table A-9. Paint deterioration rate.
1 June 1987 to 10 August 1993 exposure test series

Exp. (Days)	Test Date	Water temp (°C)	PDR (% AF Remaining)					
			F121	ABC3	D214	FBCR	FBST	FB84
1	02–June–87		100	100	100	95	100	100
8	09–June–87		100	100	100	95	100	100
15	16–June–87		100	100	100	95	100	100
30	01–July–87		100	100	100	95	100	100
63	03–Aug–87		100	100	100	92	100	100
94	03–Sept–87		100	100	100	90	99	100
128	07–Oct–87		100	100	100	90	98	100
204	22–Dec–87		100	95	100	85	95	100
268	24–Feb–88		100	75	100	82	95	100
325	21–Apr–88		100	45	100	80	95	100
387	22–June–88		100	45	100	80	90	100
448	22–Aug–88		100	45	100	80	85	100
505	18–Oct–88		100	40	100	80	75	100
570	22–Dec–88		100	25	100	80	40	100
638	28–Feb–89		100	25	100	80	34	100
696	27–Apr–89		80	25	80	80	34	100
749	19–June–89		80	20	80	80	34	100
812	21–Aug–89	20	80	15	80	75	25	100
876	24–Oct–89	20	80	15	80	70	25	100
933	20–Dec–89		80	15	80	70	25	100
1011	08–Mar–90		80	15	80	70	15	100
1074	10–May–90	21	80	10	80	70	10	90
1124	29–June–90	N/A	80	10	80	70	10	90
1155	30–July–90	N/A	80	10	80	65	10	90
1186	30–Aug–90	N/A	80	10	80	65	10	90
1217	30–Sept–90	N/A	80	10	80	60	10	80
1256	08–Nov–90	18	80	10	80	60	10	80
1317	08–Jan–91	17	80		80	60		
1466	06–June–91	20	65		80	50		
1690	16–Jan–92	17	65		80	50		
1864	08–July–92	21	96		97	48		
2068	28–Jan–93	19	98		100	31		
2262	10–Aug–93	21	94		94	35		

Exp. = Exposure time in days.
PDR = Paint Deterioration Rate. The % Area of the panel covered by AF Coating.
AF = Antifoulant painted surface.

Table A-10. Surface color.
1 June 1987 to 22 December 1988 exposure test series

Exp. (Days)	Test Date	Surface Color (% Red)					
		F121	ABC3	D214	FBCR	FBST	FB84
1	02–June–87	69	66	70	70	61	65
8	09–June–87	43	53	59	72	53	58
15	16–June–87	37	51	56	60	50	57
30	01–July–87	41	47	58	73	53	62
63	03–Aug–87	25	52	63	52	57	59
94	03–Sept–87	30	57	60	60	56	65
128	07–Oct–87	21	48	47	48	47	52
204	22–Dec–87	25	45	42	48	47	60
268	24–Feb–88	16	42	33	43	38	46
325	21–Apr–88	16	47	44	44	39	47
387	22–June–88	7	42	35	28	34	46
448	22–Aug–88	9	53	48	42	44	53
505	18–Oct–88	16	51	49	42	45	47
570	22–Dec–88	8	47	46	39	41	48

Exp. = Exposure time in days.

Table A-11. Surface pH.
1 June 1987 to 22 December 1988 exposure test series

Exp. (Days)	Test Date	Surface pH					
		F121	ABC3	D214	FBCR	FBST	FB84
1	02–June–87	8.01	7.27	7.34	8.27	6.98	8.09
8	09–June–87	8.23	7.83	7.68	8.14	7.60	8.01
15	16–June–87	7.99	7.94	7.91	8.03	7.95	7.67
30	01–July–87	7.69	8.06	7.86	7.74	7.96	7.59
63	03–Aug–87	7.86	8.39	8.22	8.18	8.19	8.66
94	03–Sept–87	7.90	8.38	8.34	8.16	8.10	8.45
128	07–Oct–87	8.19	8.47	8.45	8.24	8.36	8.28
204	22–Dec–87	8.35	8.47	8.31	8.26	8.14	8.06
268	24–Feb–88	8.34	8.41	8.43	8.43	8.13	8.40
325	21–Apr–88	8.42	8.45	8.43	8.43	8.36	8.45
387	22–June–88	8.23	8.33	8.11	8.22	8.13	7.92
448	22–Aug–88	8.20	8.35	8.29	8.22	7.93	8.40
505	18–Oct–88	7.93	8.08	8.08	8.14	7.98	7.35
570	22–Dec–88	8.12	8.25	8.20	8.08	8.00	8.26

Exp. = Exposure time in days.

Table A-12. Fouling rate.
1 June 1988 to 19 July 1993 exposure test series

			Fouling Rate (% Macrofouling/AF Remaining)					
Exp. (Days)	Test Date	Water Temp (°C)	F121	ABC3	ABC3	ABC3	BRA540	BRA540
1	02–June–88		0	0	0	0	0	0
7	08–June–88		0	0	0	0	0	0
14	15–June–88		0	0	0	0	0	0
34	05–July–88		0	0	0	0	0	0
63	03–Aug–88		0	0	0	0	0	0
104	13–Sept–88		0	0	0	0	0	0
133	12–Oct–88		0	0	0	0	0	0
167	15–Nov–88		0	0	0	0	0	0
196	14–Dec–88		0	0	0	0	0	0
258	14–Feb–89		0	0	0	0	0	0
314	11–Apr–89		0	0	0	0	0	0
376	12–June–89		0	0	0	0	0	0
441	16–Aug–89	21	0	0	0	0	0	0
509	23–Oct–89	20	0	0	0	0	0	0
566	19–Dec–89		0	0	0	0	0	0
610	01–Feb–90		0	0	0	0	0	0
706	08–May–90	21	0	0	0	0	0	0
728	30–May–90	N/A	0	0	0	0	0	0
758	29–June–90	N/A	0	0	0	0	0	0
789	30–July–90	N/A	5	0	5	5	5	5
820	30–Aug–90	N/A	5	0	5	5	0	0
851	30–Sept–90	N/A	5	0	5	5	0	0
889	07–Nov–90	19	5	0	5	5	0	0
950	07–Jan–91	17	5	0	5	10	5	5
1006	04–Mar–91	19	5	0	5	10	5	5
1070	07–May–91	19	10	5	5	10	5	5
1135	11–July–91	21	20	5	5	lost	5	5
1197	11–Sept–91	21	20	5	5		5	5
1266	19–Nov–91	20	30	15	5		10	10
1325	17–Jan–92	17	35	15	10		10	10
1386	18–Mar–92	19	40	15	10		10	10
1477	17–June–92	21	13	1	1		1	1
1539	18–Aug–92	24	9	4	1		1	1
1602	20–Oct–92	21	11	0	1		0	0
1661	18–Dec–92	18	10	0	2		0	0
1722	17–Feb–93	17	3	0	0		0	0
1784	20–Apr–93	20	13	2	0		0	0
1874	19–July–93	22	12	4	4		1	1

Exp. = Exposure time in days.
AF = Antifoulant painted surface.

Table A-13. Leaching rate.
1 June 1988 to 19 July 1993 exposure test series

			Leaching Rate (µg-Cu/cm²/day)					
Exp. (Days)	Test Date	Water Temp (°C)	F121	ABC3	ABC3	ABC3	BRA540	BRA540
1	02–June–88		31	35	33	26	15	16
7	08–June–88		61	60	56	64	32	32
14	15–June–88		42	53	46	44	31	30
34	05–July–88		22	17	19	20	20	18
63	03–Aug–88		17	20	23	24	19	19
104	13–Sept–88		13	20	21	24	21	19
133	12–Oct–88		8	20	22	22	21	19
167	15–Nov–88		12	17	16	21	16	15
196	14–Dec–88		5	19	22	21	18	13
258	14–Feb–89		2	16	16	18	12	11
314	11–Apr–89		5	14	18	22	14	18
376	12–June–89		6	13	14	10	18	11
441	16–Aug–89	21	18	19	15	18	14	14
509	23–Oct–89	20	7	12	11	10	13	12
566	19–Dec–89		4	12	11	9	12	19
610	01–Feb–90		5	11	10	N/A	11	10
706	08–May–90	21	10	13	7	10	7	11
769	10–July–90	23	21	21	14	21	17	16
832	11–Sept–90	23	0	11	6	8	6	5
889	07–Nov–90	19	1	7	9	10	8	8
950	07–Jan–91	17	0	9	9	10	7	7
1006	04–Mar–91	19	1	8	7	9	8	4
1070	07–May–91	19	1	13	6	6	6	6
1135	11–July–91	21	11	5	10	lost	7	6
1197	11–Sep–91	21	2	9	11		7	7
1266	19–Nov–91	20	3	15	9		4	4
1325	17–Jan–92	17	2	6	6		6	5
1386	18–Mar–92	19	1	6	8		6	6
1477	17–June–92	21	12	13	9		9	7
1539	18–Aug–92	24	0	6	6		7	8
1602	20–Oct–92	21	5	5	7		6	6
1661	18–Dec–92	18	5	6	6		4	5
1722	17–Feb–93	17	2	4	5		6	5
1784	20–Apr–93	20	4	6	6		5	6
1874	19–July–93	22	2	6	6		5	4

Exp. = Exposure time in days.
Leaching Rate (in µg-Cu/Cm2/day) where
[A = (Panel Area) – (Eroded/Peeled-off Area + Area covered by macro-fouling)]

Table A-14. Paint deterioration rate.
1 June 1988 to 19 July 1993 exposure test series

			PDR (% AF Remaining/Original Panel Area)					
Exp. (Days)	Test Date	Water Temp (°C)	F121	ABC3	ABC3	ABC3	BRA540	BRA540
1	02–June–88		100	100	100	100	100	100
7	08–June–88		100	100	100	100	100	100
14	15–June–88		100	100	100	100	100	100
34	05–July–88		100	100	100	100	100	100
63	03–Aug–88		100	100	100	100	100	100
104	13–Sept–88		100	100	100	100	100	100
133	12–Oct–88		100	100	100	100	100	100
167	15–Nov–88		100	100	100	100	100	100
196	14–Dec–88		100	100	100	100	100	100
258	14–Feb–89		100	100	100	100	100	100
314	11–Apr–89		100	100	100	100	100	100
376	12–June–89		100	100	100	100	100	100
441	16–Aug–89	21	100	100	100	100	100	100
509	23–Oct–89	20	100	100	100	100	100	100
566	19–Dec–89		100	100	100	100	100	100
610	01–Feb–90		100	100	100	100	100	100
706	08–May–90	21	90	95	100	95	100	98
728	30–May–90	N/A	90	95	100	95	100	98
758	29–June–90	N/A	90	95	100	95	100	98
789	30–July–90	N/A	90	95	100	95	100	98
820	30–Aug–90	N/A	90	95	100	95	100	98
851	30–Sept–90	N/A	90	95	100	95	100	98
889	07–Nov–90	19	90	95	100	95	100	98
950	07–Jan–91	17	90	95	100	95	100	98
1006	04–Mar–91	19	90	95	100	95	100	98
1070	07–May–91	19	90	95	100	95	100	98
1135	11–July–91	21	90	95	100	lost	98	98
1197	11–Sept–91	21	90	95	99		98	98
1266	19–Nov–91	20	90	95	97		98	98
1325	17–Jan–92	17	90	95	97		98	98
1386	18–Mar–92	19	90	95	97		98	98
1477	17–June–92	21	99	97	98		100	100
1539	18–Aug–92	24	96	95	96		100	100
1602	20–Oct–92	21	95	90	93		100	100
1661	18–Dec–92	18	90	87	94		100	100
1722	17–Feb–93	17	93	87	93		100	100
1784	20–Apr–93	20	93	87	92		100	100
1874	19–July–93	22	89	87	92		100	100

Exp. = Exposure time in days.
PDR = Paint Deterioration Rate. The % Area of the panel covered by AF Coating.
AF = Antifoulant painted surface.

Table A-15. Surface color.
1 June 1988 to 14 December 1988 exposure time series

		Surface Color (% Red)					
Exp. (Days)	**Test Date**	**F121**	**ABC3**	**ABC3**	**ABC3**	**BRA540**	**BRA540**
1	02–June–88		53	55	55	46	48
7	08–June–88	38	44	49	48	49	50
14	15–June–88	29	38	35	34	35	45
34	05–July–88	54	72	78	87	71	67
63	03–Aug–88	*		37	34	33	30
104	13–Sept–88	30*	61	59	56	59	57
133	12–Oct–88	31*	57		53	43	57
167	15–Nov–88	5*	42	40	31	48	48
196	14–Dec–88	*	11	20	10	36	37

*F121 turned grayish green within 2-months exposure. This color is different and more difficult to measure than the greenish color developed on exposure of some other F121 samples, including those in the 1 June 1987 test series. The original color of this series was also different from the majority of formulas we encountered in the past. This is a purplish red rather than bright cherry red color.

Exp. = Exposure time in days.

Table A-16. Surface pH.
1 June 1988 to 14 December 1988 exposure test series

		Surface pH					
Exp. (Days)	**Test Date**	**F121**	**ABC3**	**ABC3**	**ABC3**	**BRA540**	**BRA540**
1	02–June–88	7.79	8.00	8.00	7.94	7.73	7.79
7	08–June–88	8.19	8.17	8.10	8.06	8.05	8.20
14	15–June–88	8.27	8.28	8.29	8.33	8.20	8.08
34	05–July–88	8.46	8.34	8.32	8.42	8.49	8.21
63	03–Aug–88	8.22	8.48	8.36	8.40	8.34	8.46
104	13–Sept–88	8.18	8.22	8.34	8.38	8.17	8.30
133	12–Oct–88	8.18	8.11	7.99	7.95	8.10	8.12
167	15–Nov–88	7.99	7.94	7.93	7.92	8.13	8.07
196	14–Dec–88	8.26	8.17	8.17	8.16	8.29	8.29

Exp. = Exposure time in days.

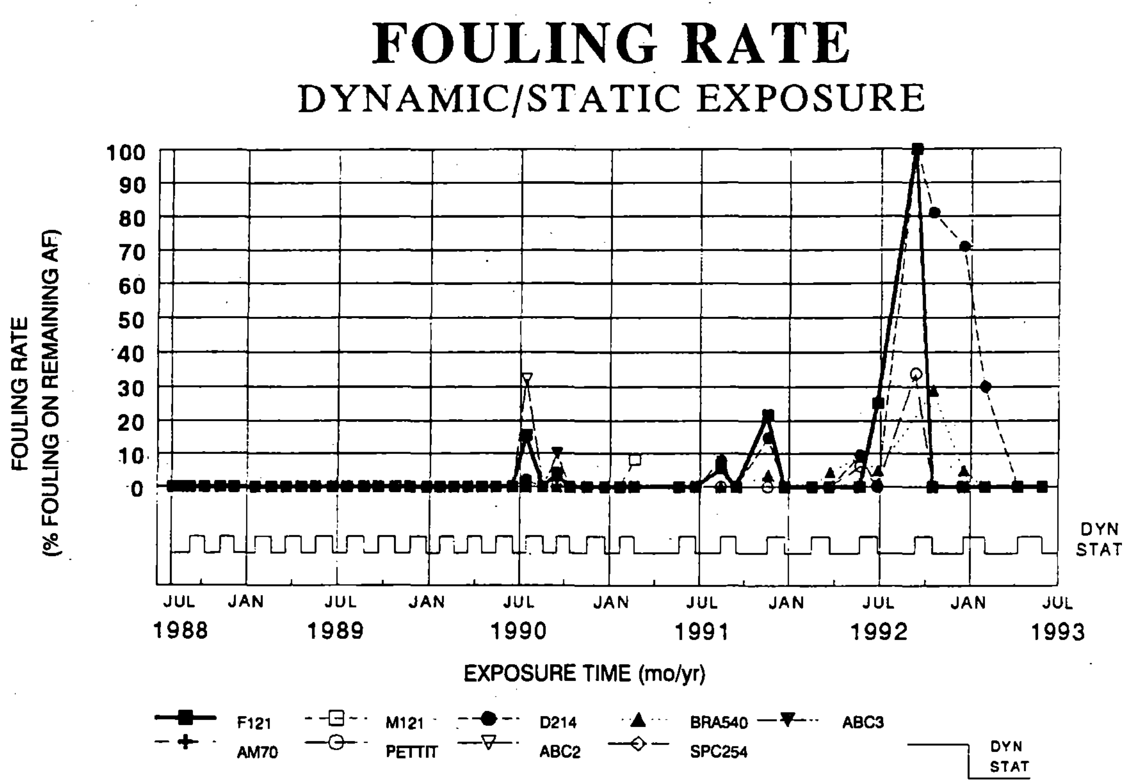
Table A-17. Ameron 70.
27 February 1989 to 9 July 1991 static exposure test series

Exp. (Days)	Test Date	Water Temp (°C)	Fouling Rate (% Macrofouling)		Leaching Rate (μg-Cu/Cm²/day)		PDR (% AF Remaining)	
			F121	AM70	F121	AM70	F121	AM70
3	1–Mar–89		0	0	55	9	100	100
7	6–Mar–89		0	0	55	21	100	100
14	13–Mar–89		0	0	41	34	100	100
28	27–Mar–89		0	0	31	53	100	100
58	26–Apr–89		0	0	27	25	100	100
86	24–May–89		0	0	23	21	100	100
121	28–June–89		0	0	19	14	100	100
150	27–July–89		0	0	37	19	100	100
184	28–Aug–89			0		13		100
213	28–Sept–89			0		12		100
246	31–Oct–89			0		5		100
276	29–Nov–89			0		6		100
311	02–Jan–90			0		5		100
338	29–Jan–90			0		3		100
366	26–Feb–90			0		3		100
395	27–Mar–90			0		4		100
424	25–Apr–90			0		6		100
452	23–May–90	21		0		3		90
486	26–June–90	23		0		3		90
514	24–July–90	22		30		4		90
549	28–Aug–90	22		25		3		90
577	25–Sept–90	22		30		4		90
605	23–Oct–90	21		30		3		90
640	27–Nov–90	18		30		1		90
676	03–Jan–91	17		30		3		90
863	09–July–91			40		7		90

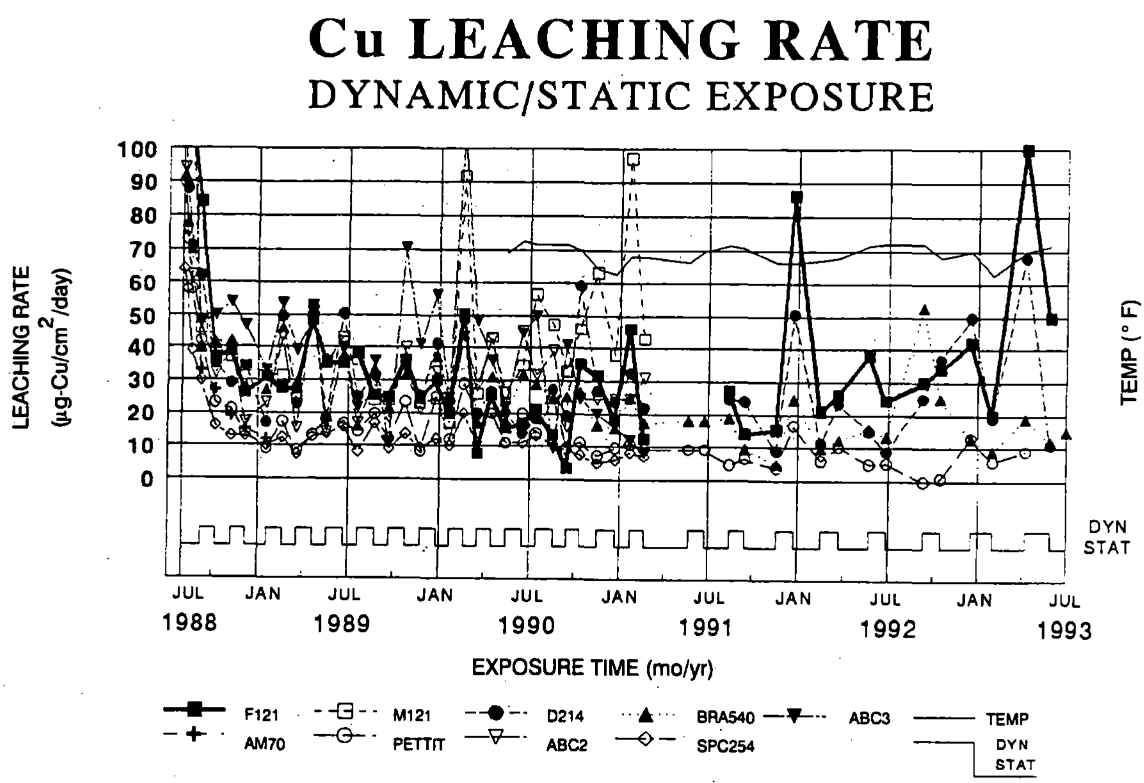
Exp. = Exposure time in days.
PDR = Paint Deterioration Rate. The % Area of the panel covered by AF Coating.
AF = Antifoulant painted surface.

APPENDIX B

GRAPHS



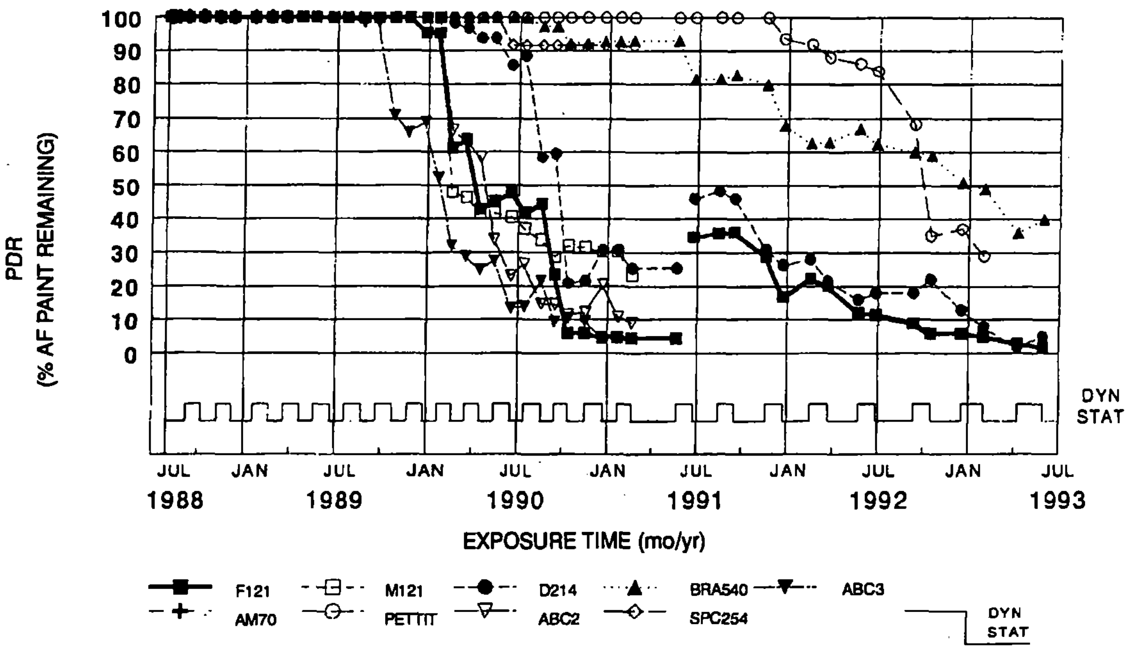
Graph B-1. Fouling rate in dynamic/static exposure tests from July 1988 to July 1993.



Graph B-2. Cu leaching rate in dynamic/static exposure tests from July 1988 to July 1993.

AF PAINT DETERIORATION RATE

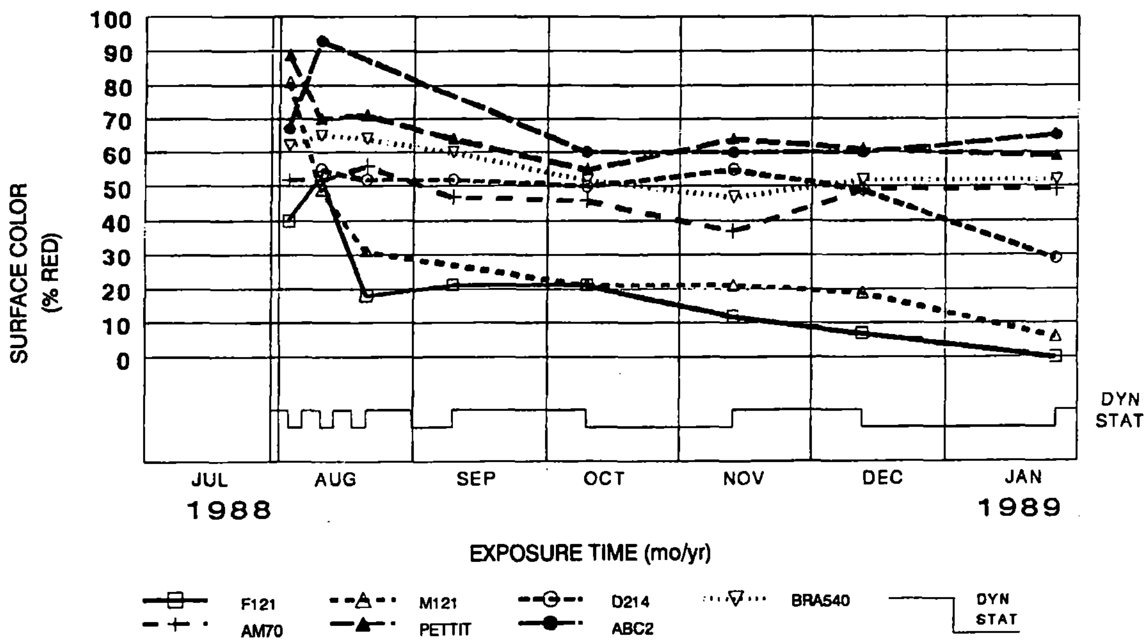
DYNAMIC/STATIC EXPOSURE



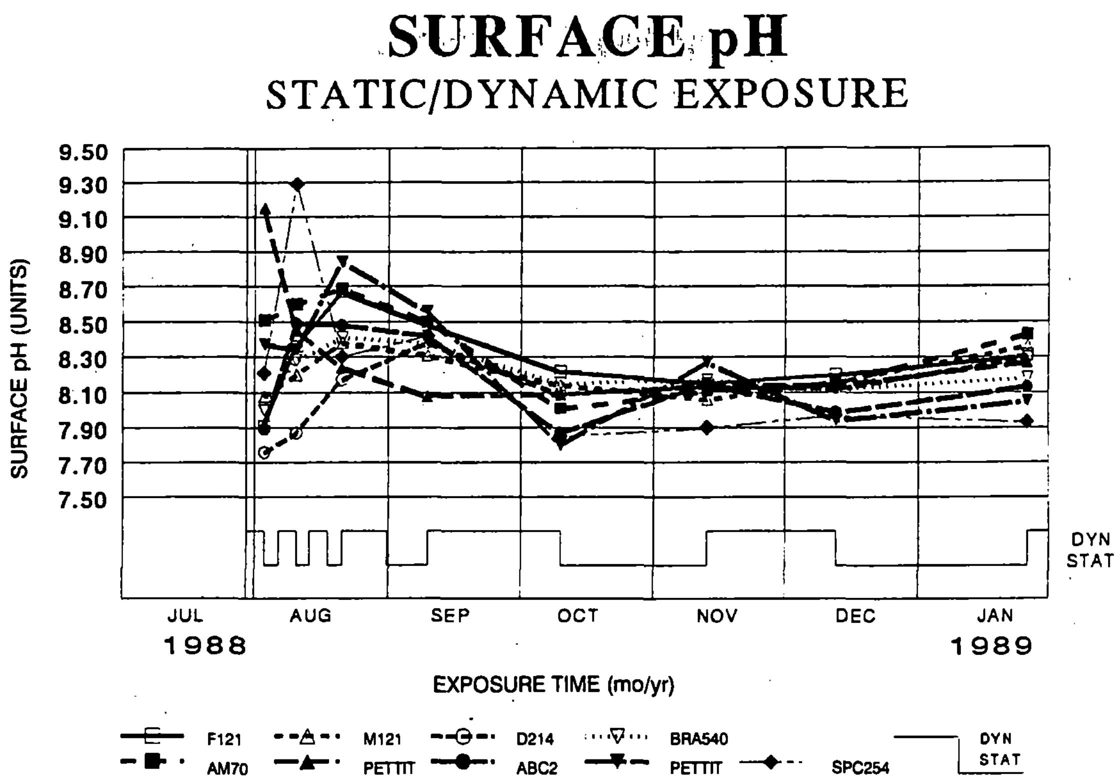
Graph B-3. Antifoulant (AF) paint deterioration rate (PDR) in dynamic/static exposure tests from July 1988 to July 1993.

SURFACE COLOR: (% RED)

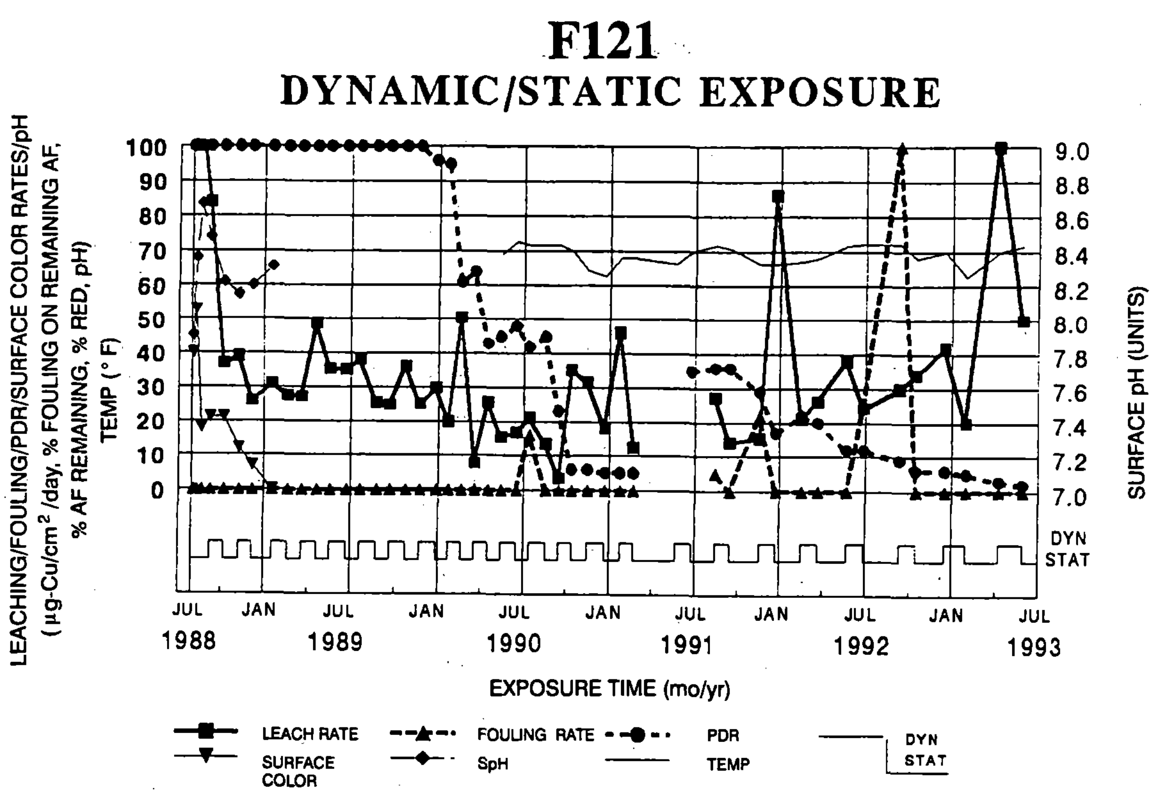
STATIC/DYNAMIC EXPOSURE



Graph B-4. Surface color (% red) in static/dynamic exposure tests from August 1988 to January 1989.

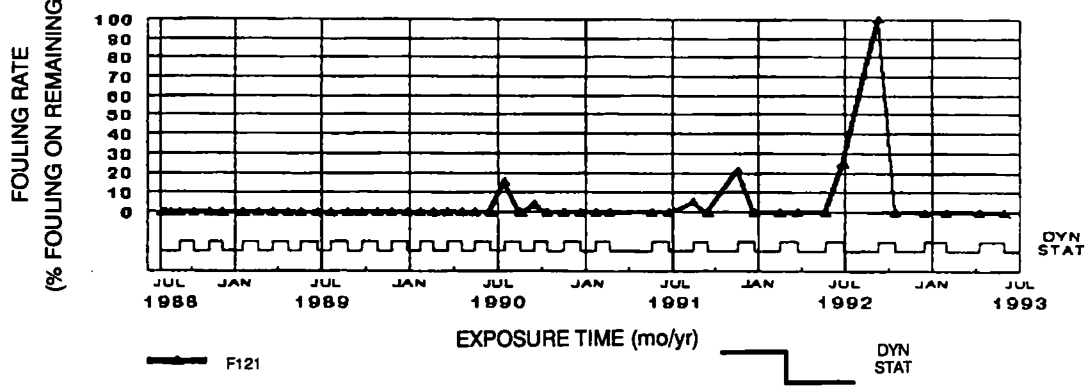


Graph B-5. Surface pH in static/dynamic exposure tests from August 1988 to January 1989.

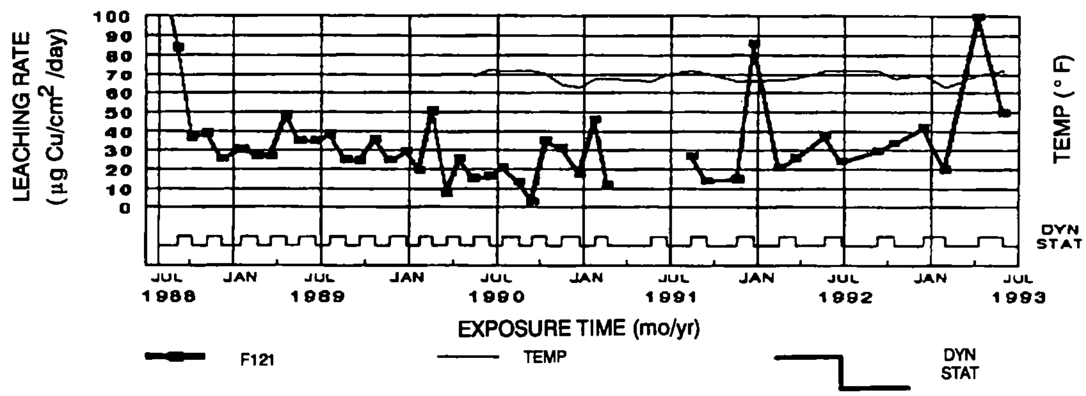


Graph B-6. Static exposure tests for F121 from July 1988 to July 1993.

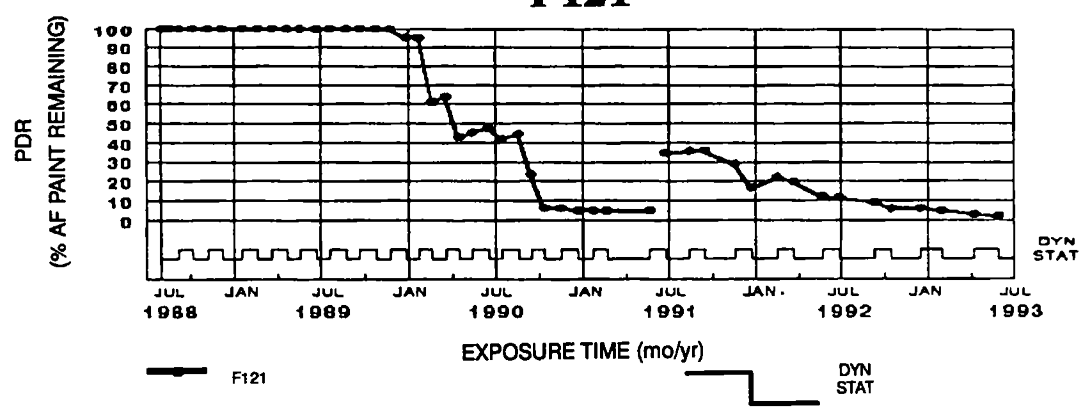
FOULING RATE
F121



Cu LEACHING RATE
F121

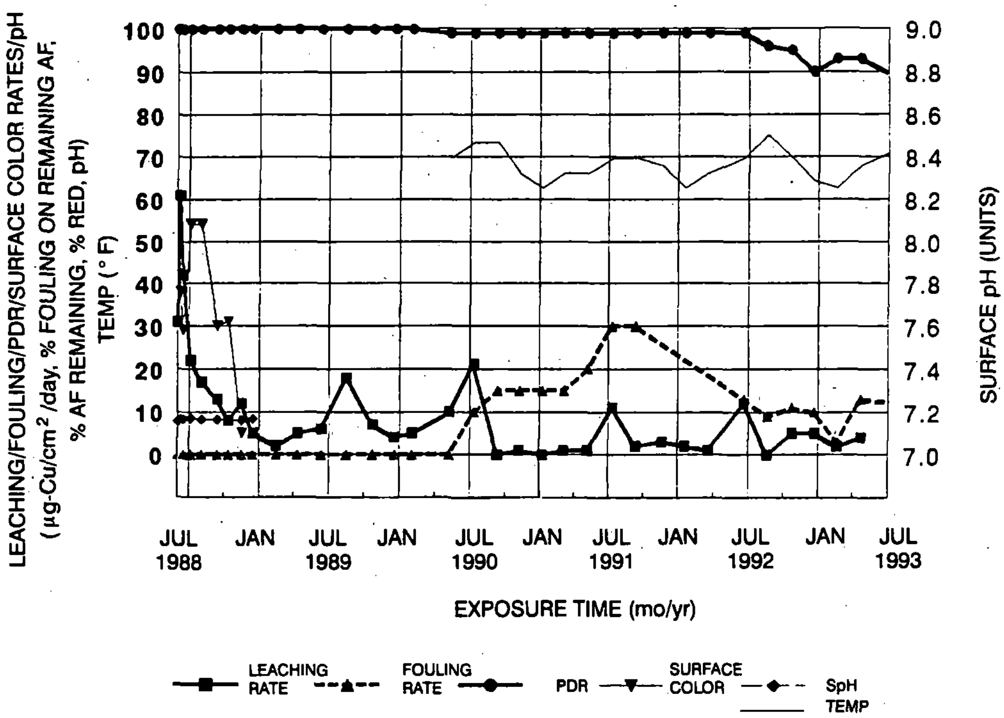


AF PAINT DETERIORATION RATE
F121

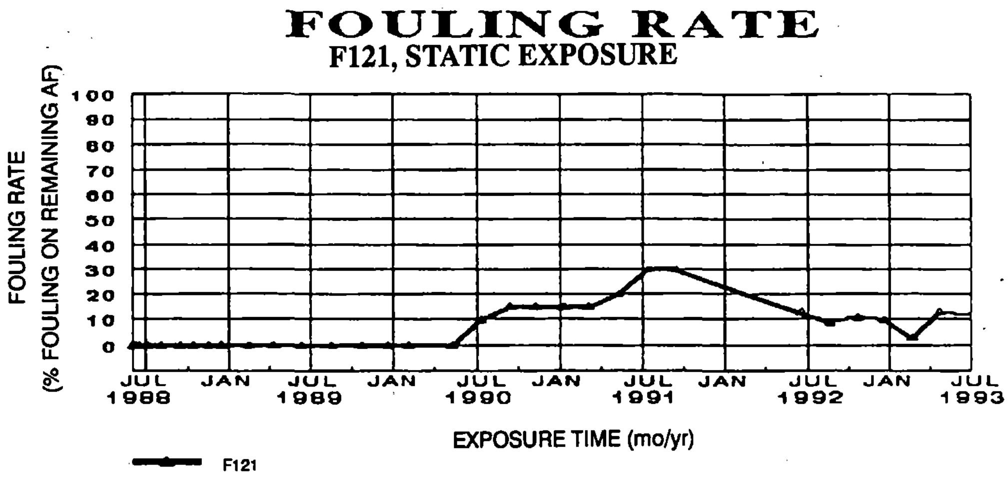


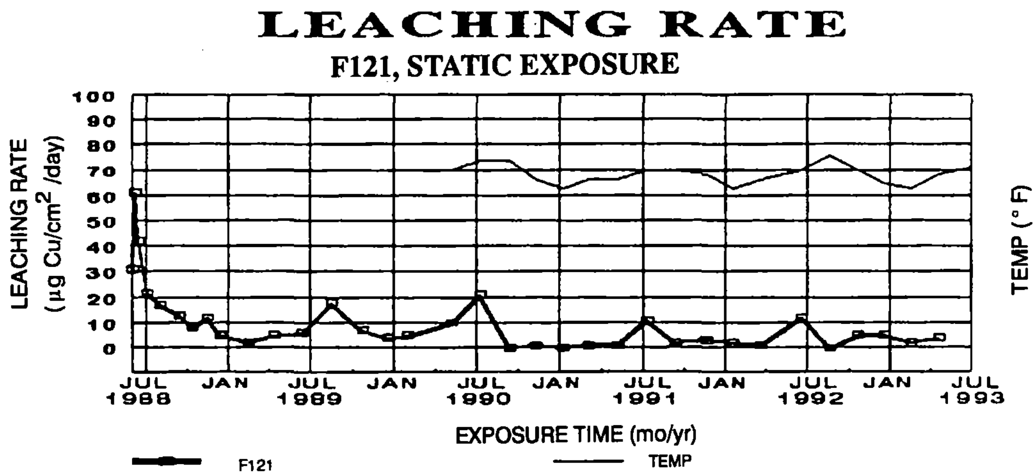
Graph B-7. Fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) for F121 in dynamic/static tests from July 1988 to July 1993.

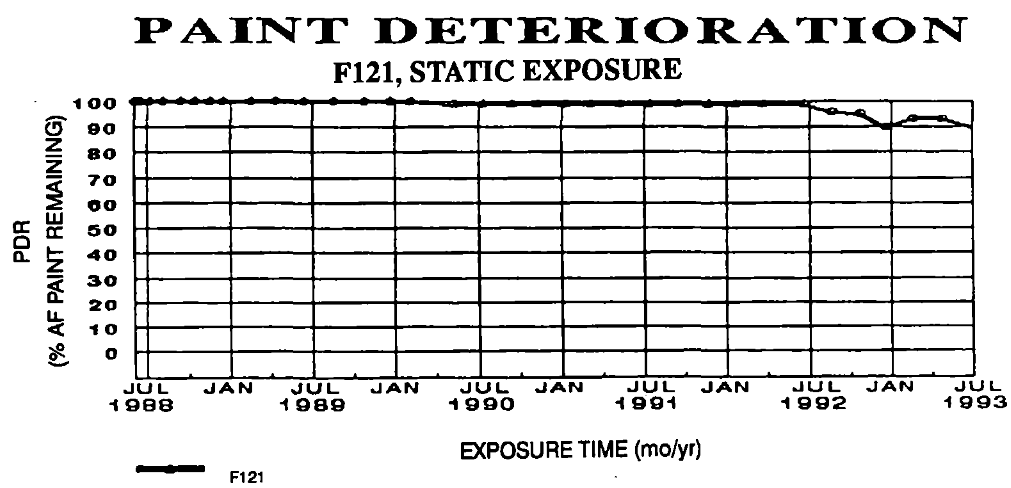
F121
STATIC EXPOSURE



Graph B-8. Static exposure tests for F121 from July 1988 to July 1993.

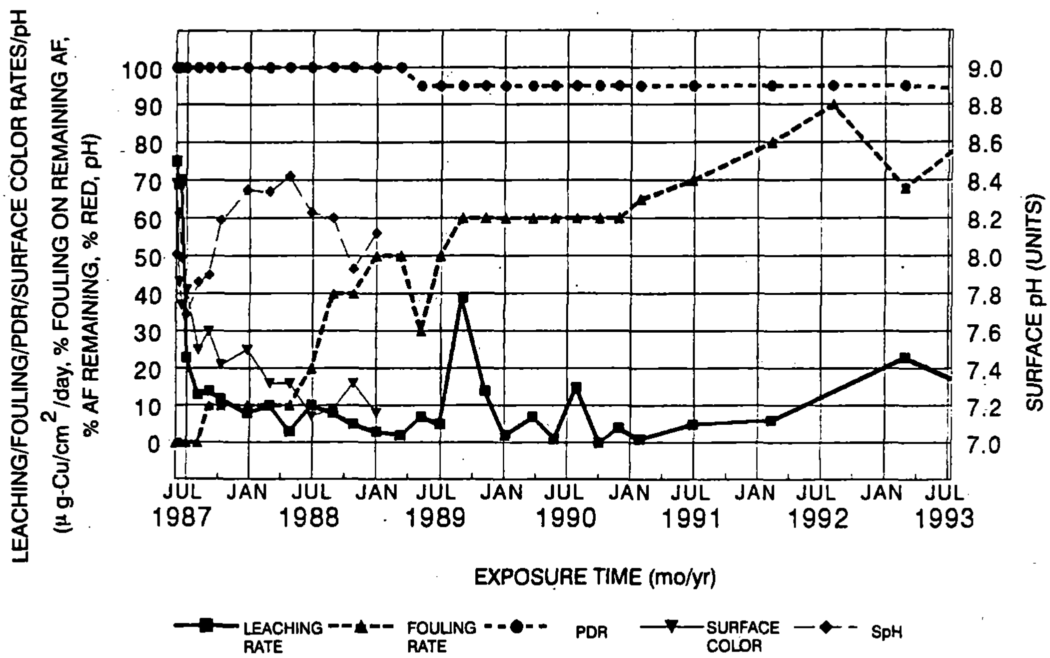






Graph B-9. Fouling rate, leaching rate, paint deterioration rate for F121 in static tests from July 1988 to July 1993.

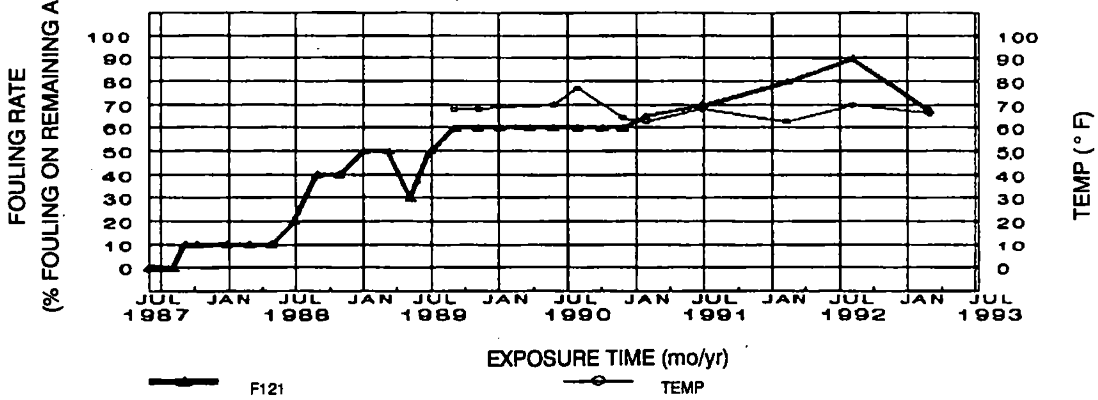
F121
STATIC EXPOSURE



Graph B-10. Static exposure tests for F121 from July 1987 to July 1993.

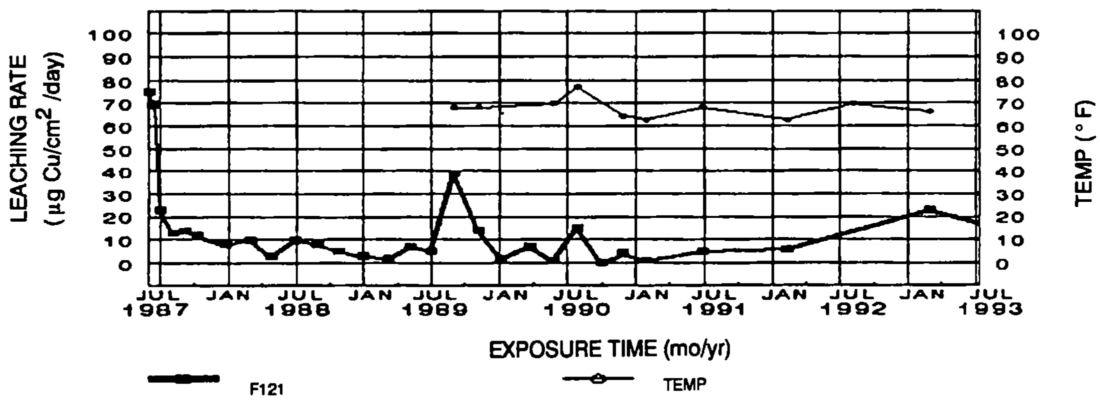
FOULING RATE

F121, STATIC EXPOSURE



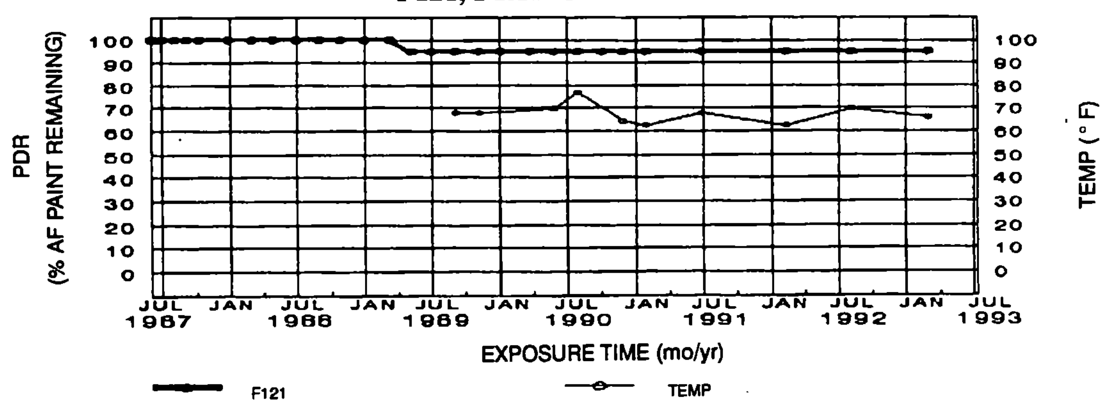
LEACHING RATE

F121, STATIC EXPOSURE

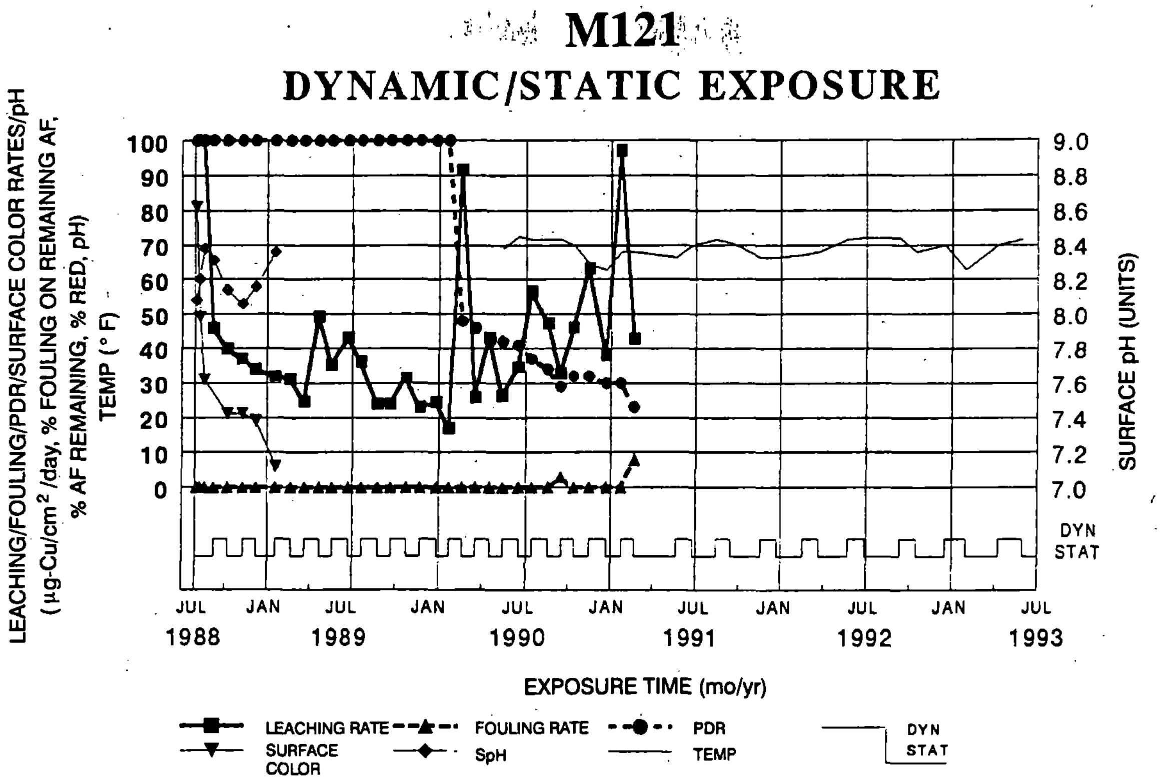


PAINT DETERIORATION

F121, STATIC EXPOSURE



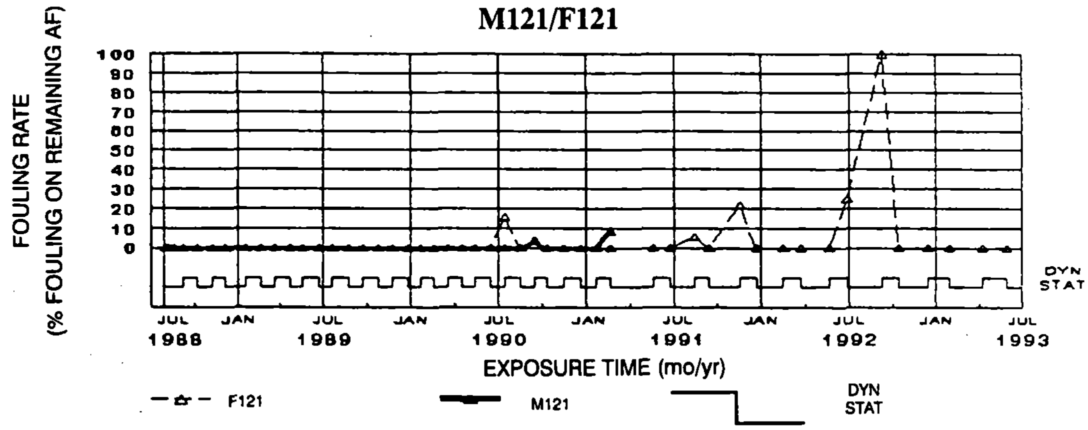
Graph B-11. Fouling rate, leaching rate, paint deterioration rate (PDR) for F121 in static tests from July 1987 to July 1993.



Graph B-12. Dynamic/static exposure tests for M121 from July 1988 to July 1993.

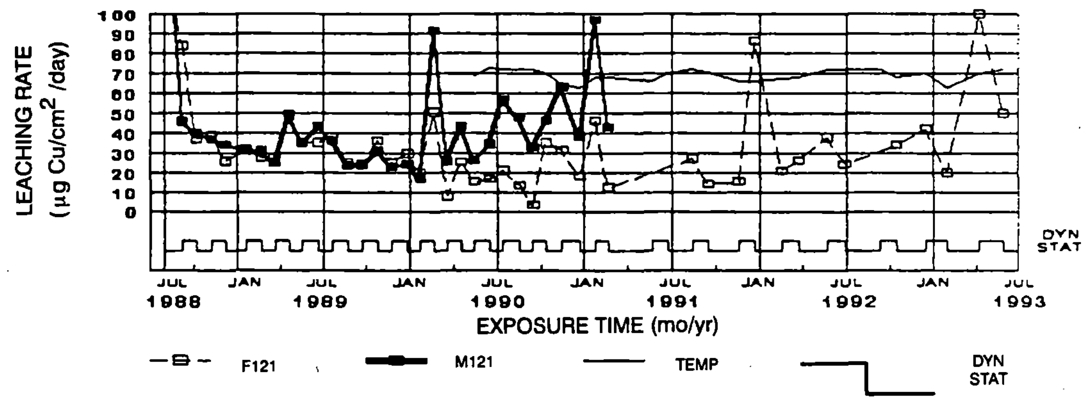
FOULING RATE

M121/F121



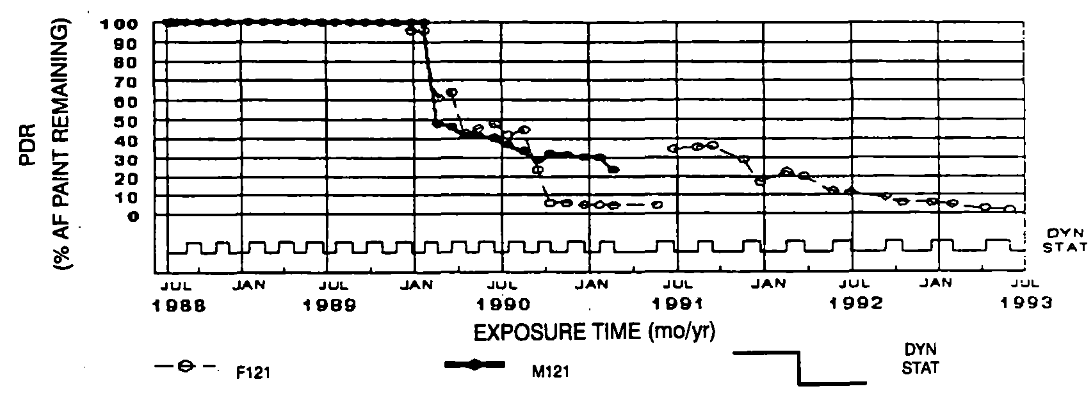
Cu LEACHING RATE

M121/F121



AF PAINT DETERIORATION RATE

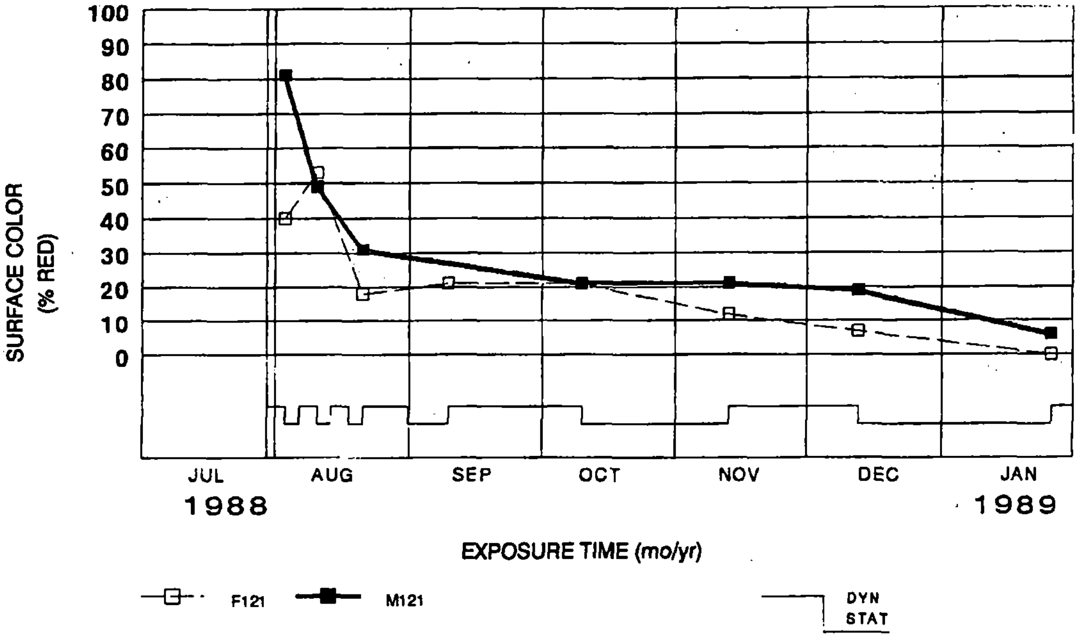
M121/F121



Graph B-13. Comparison of M121 and F121 fouling rate, Cu leaching rate, AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

SURFACE COLOR: (% RED)

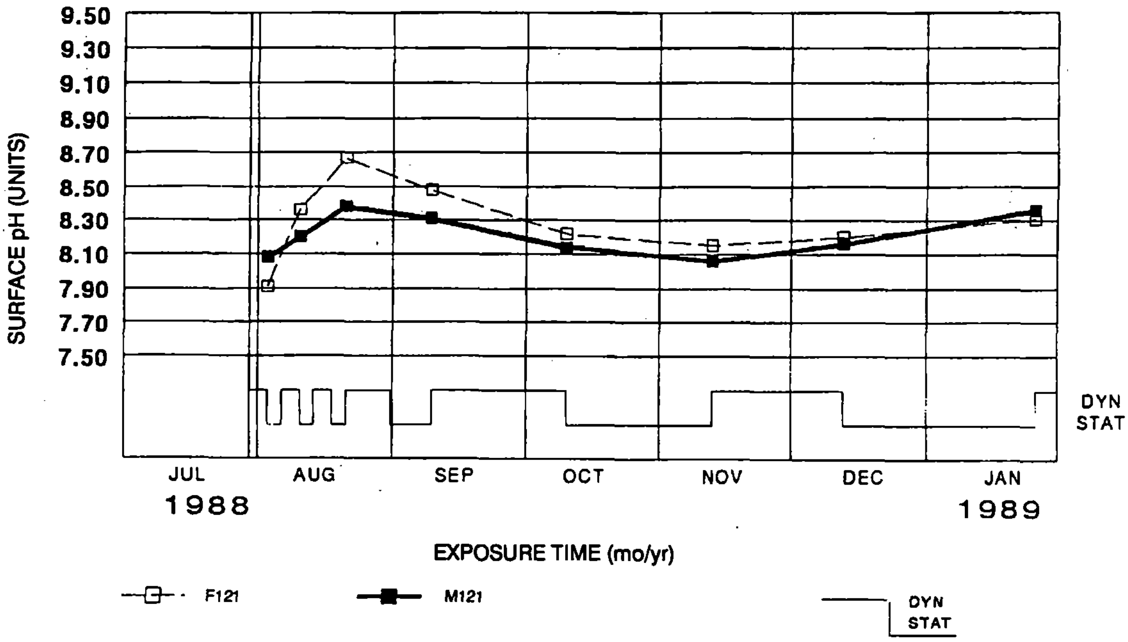
M121/F121



Graph B-14. Comparison of M121 and F121 surface color (% red) deterioration in dynamic/static tests from August 1988 to January 1989.

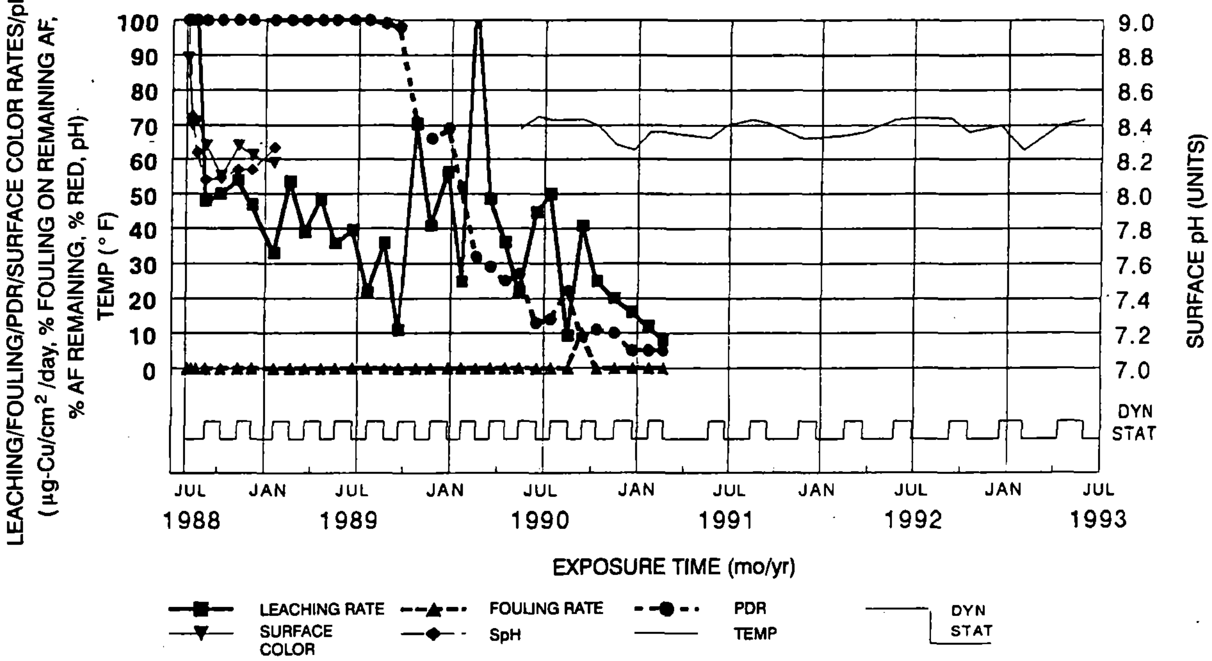
SURFACE pH

M121/F121



Graph B-15. Comparison of M121 and F121 surface pH in dynamic/static tests from August 1988 to January 1989.

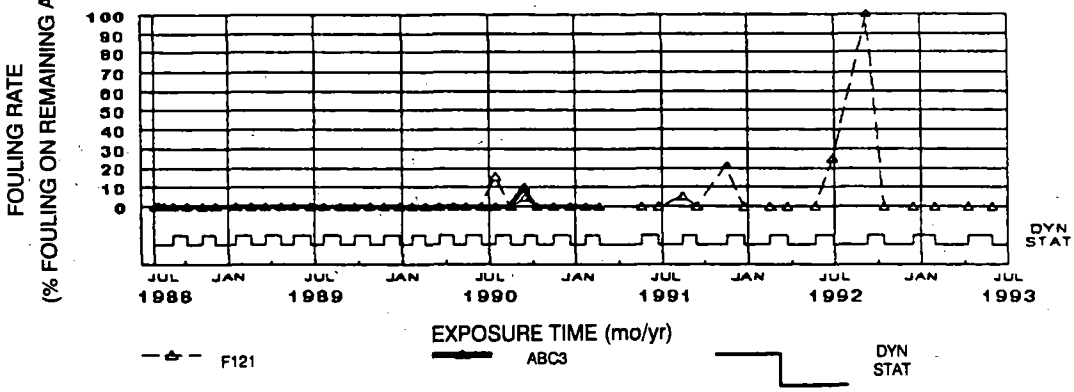
ABC3
DYNAMIC/STATIC EXPOSURE



Graph B-16. Dynamic/static exposure tests for ABC3 from July 1988 to July 1993.

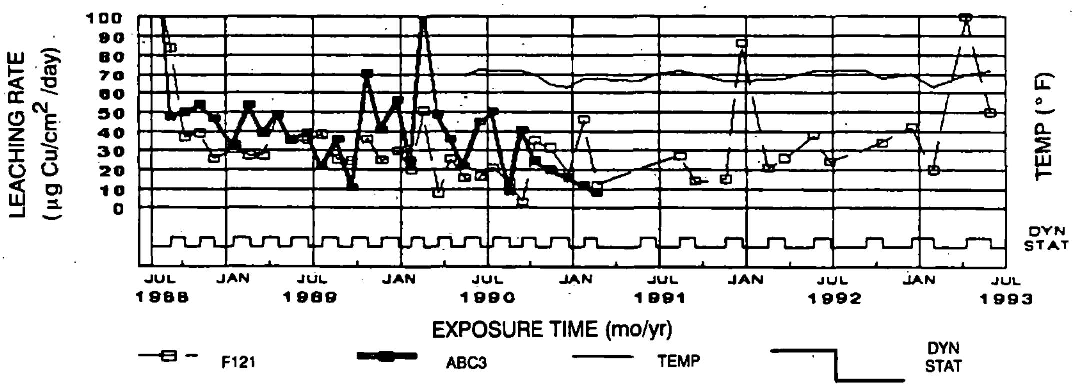
FOULING RATE

ABC3/F121



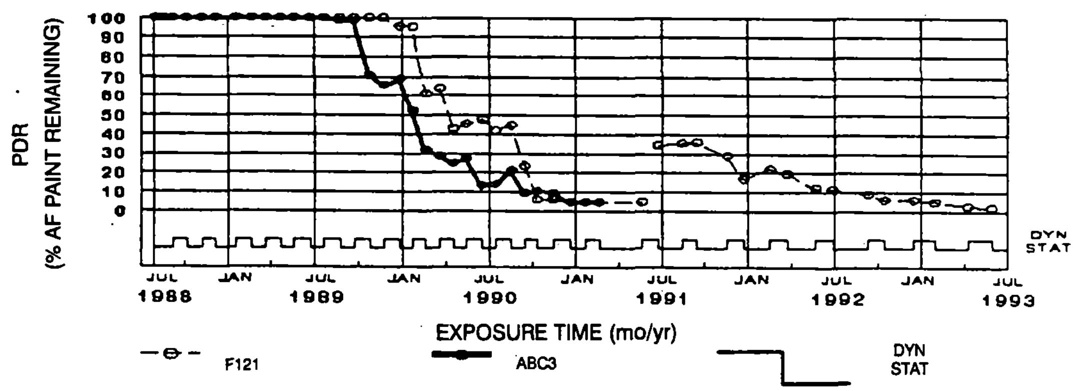
Cu LEACHING RATE

ABC3/F121



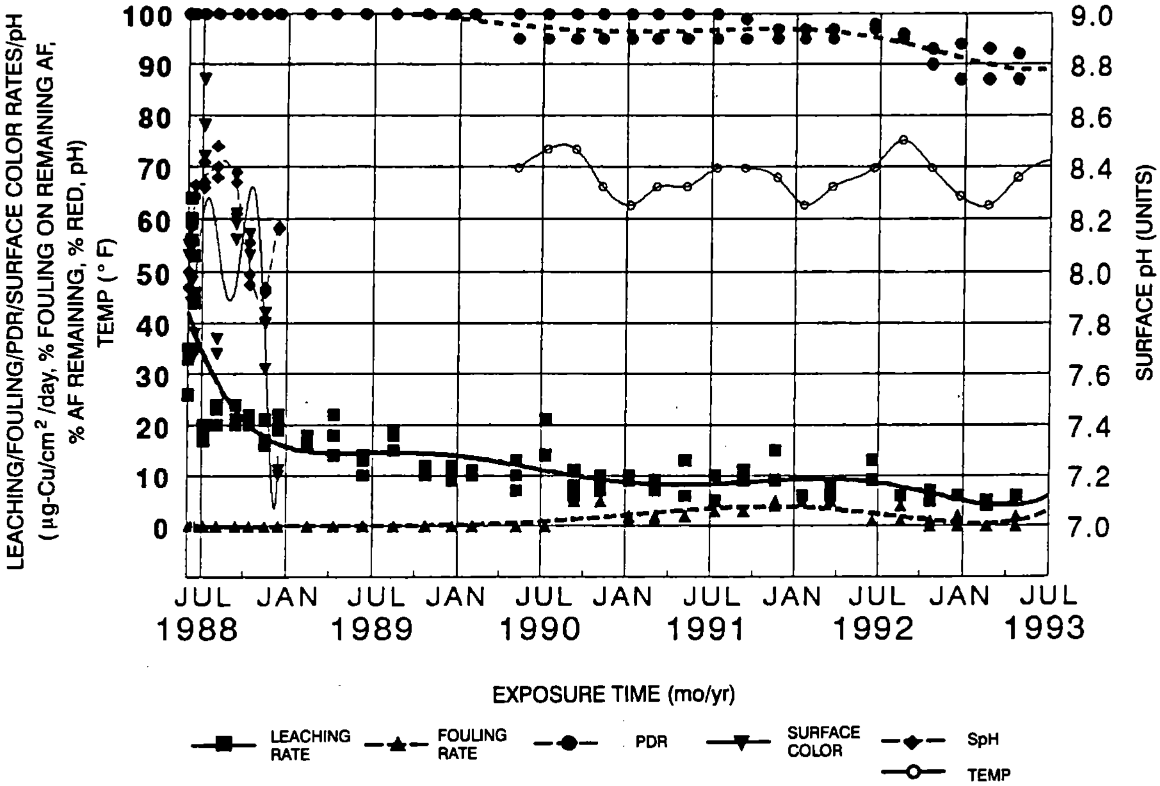
AF PAINT DETERIORATION RATE

ABC3/F121



Graph B-17. Comparison of ABC3 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

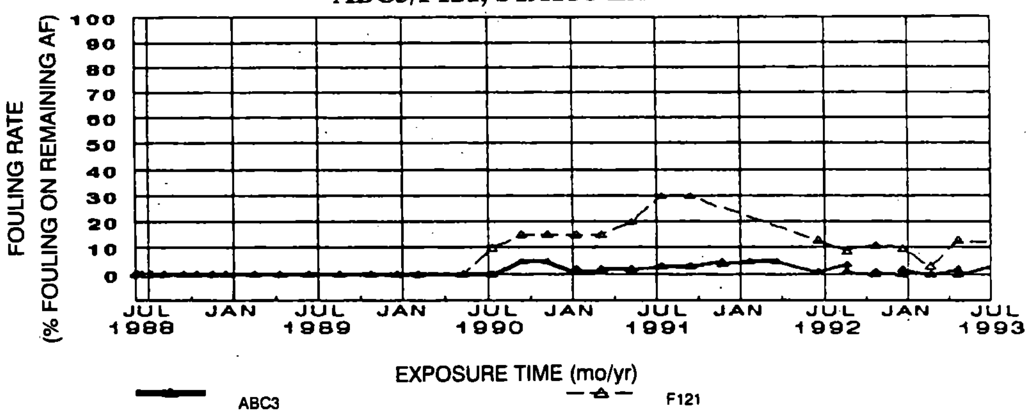
ABC3
STATIC EXPOSURE



Graph B-18. Static exposure tests for ABC3 from July 1988 to July 1993.

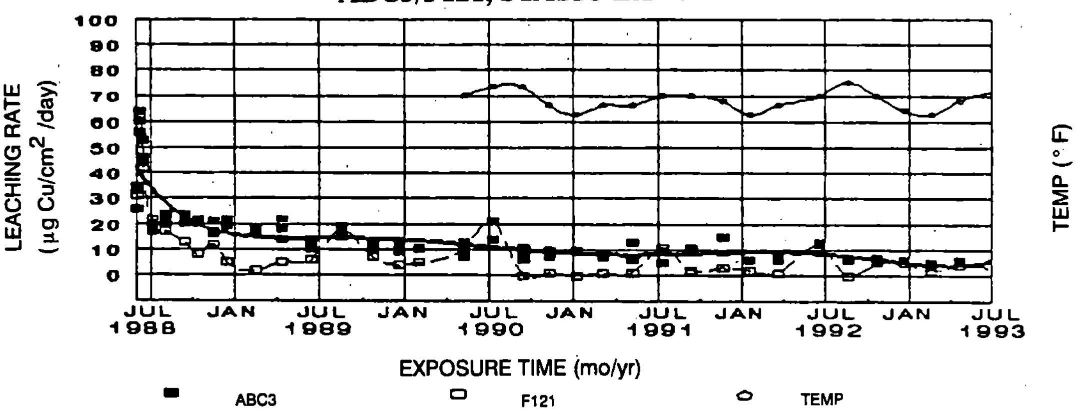
FOULING RATE

ABC3/F121, STATIC EXPOSURE



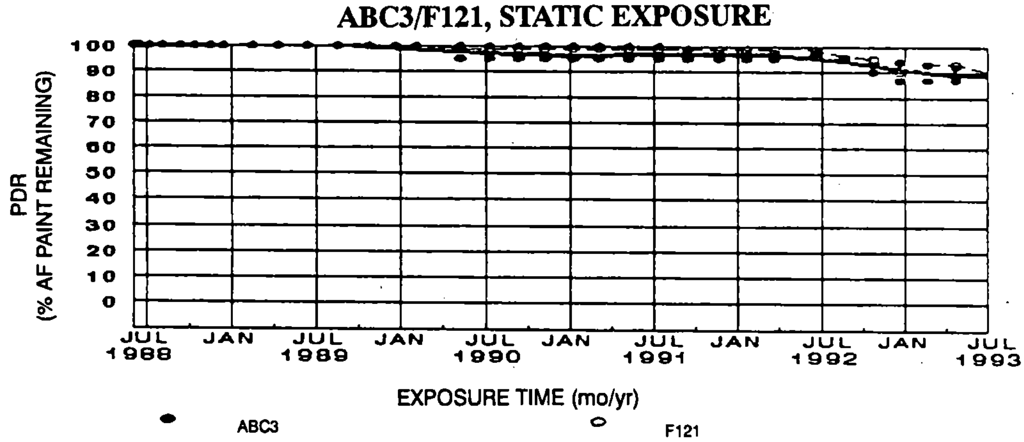
LEACHING RATE

ABC3/F121, STATIC EXPOSURE



PAINT DETERIORATION

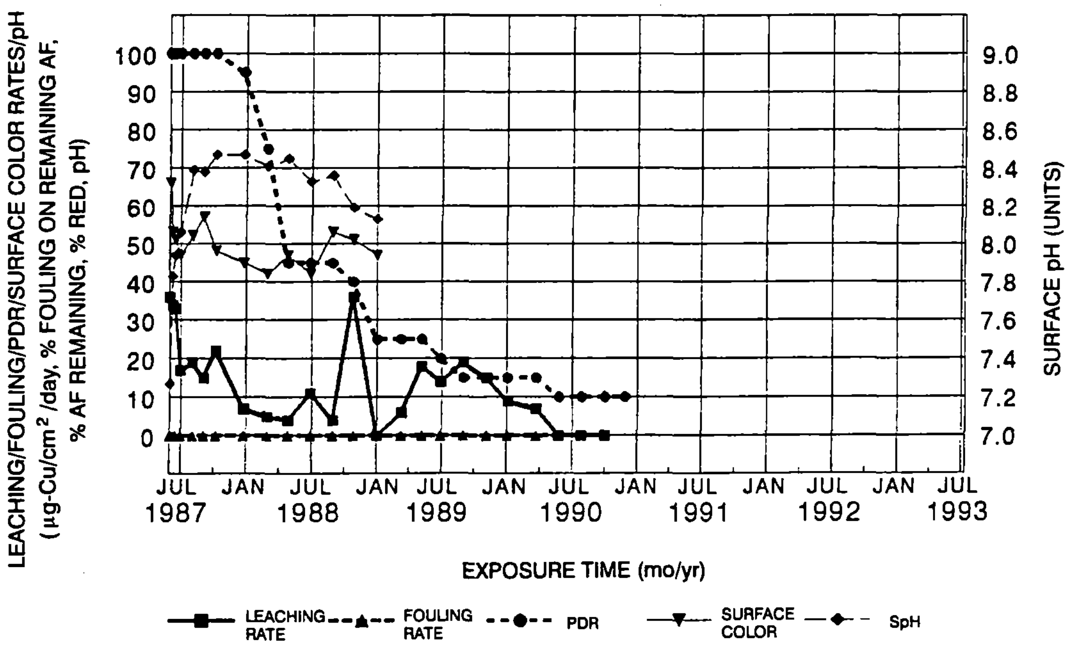
ABC3/F121, STATIC EXPOSURE



Graph B-19. Comparison of ABC3 and F121 fouling rate, leaching rate, and AF paint deterioration rate (PDR) in static exposure tests from July 1988 to July 1993.

ABC3

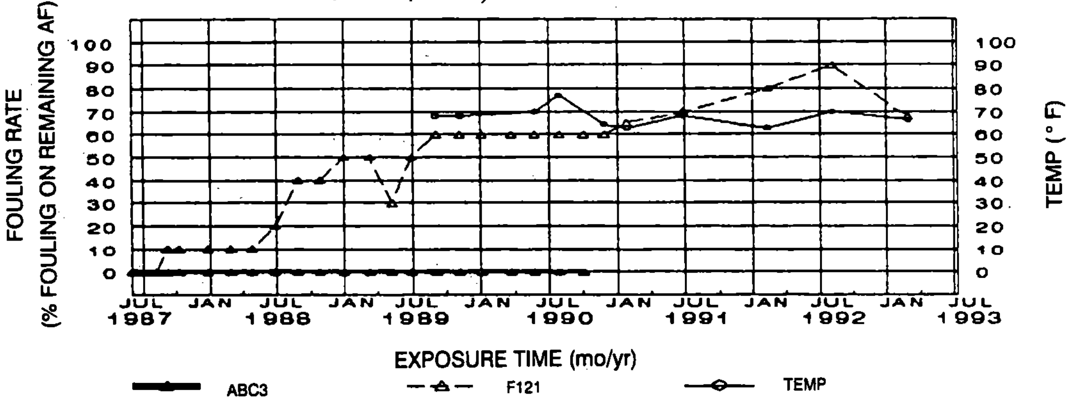
STATIC EXPOSURE



Graph B-20. Static exposure tests for ABC3 from July 1987 to July 1993.

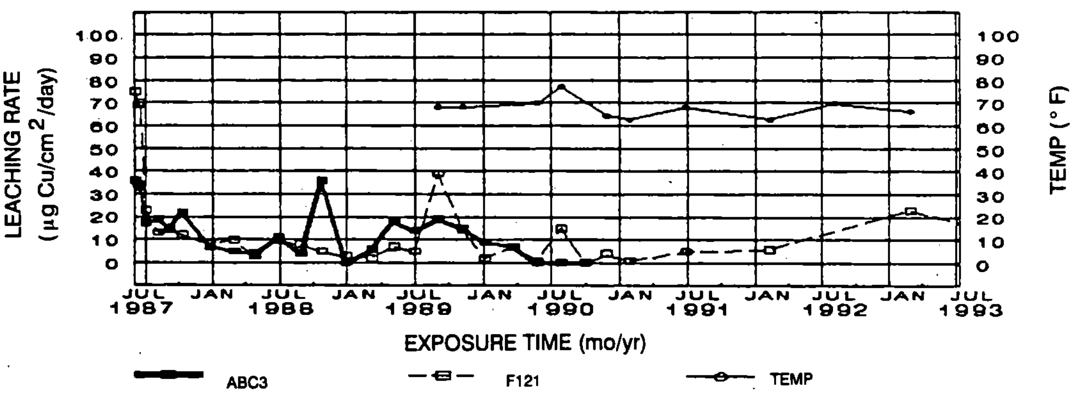
FOULING RATE

ABC3/F121, STATIC EXPOSURE



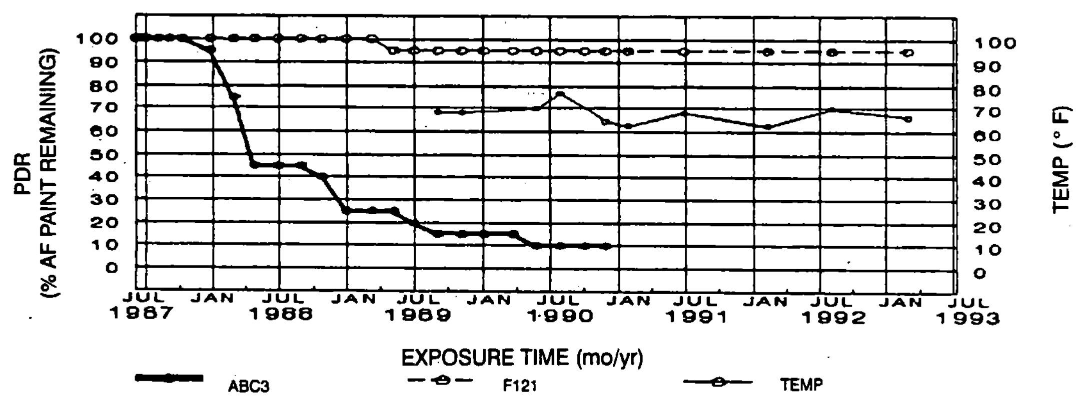
LEACHING RATE

ABC3/F121, STATIC EXPOSURE

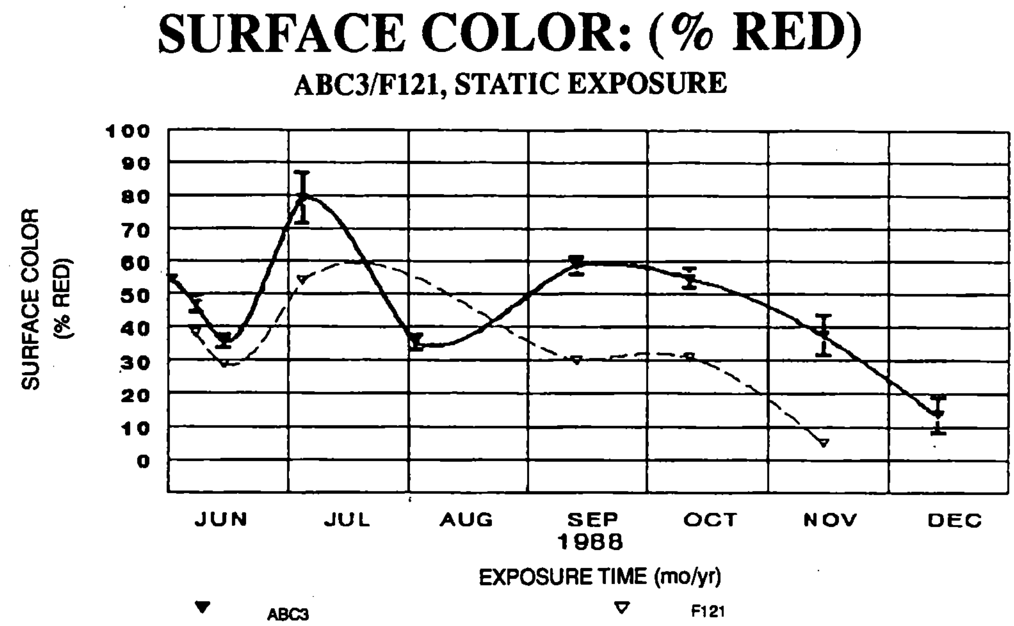


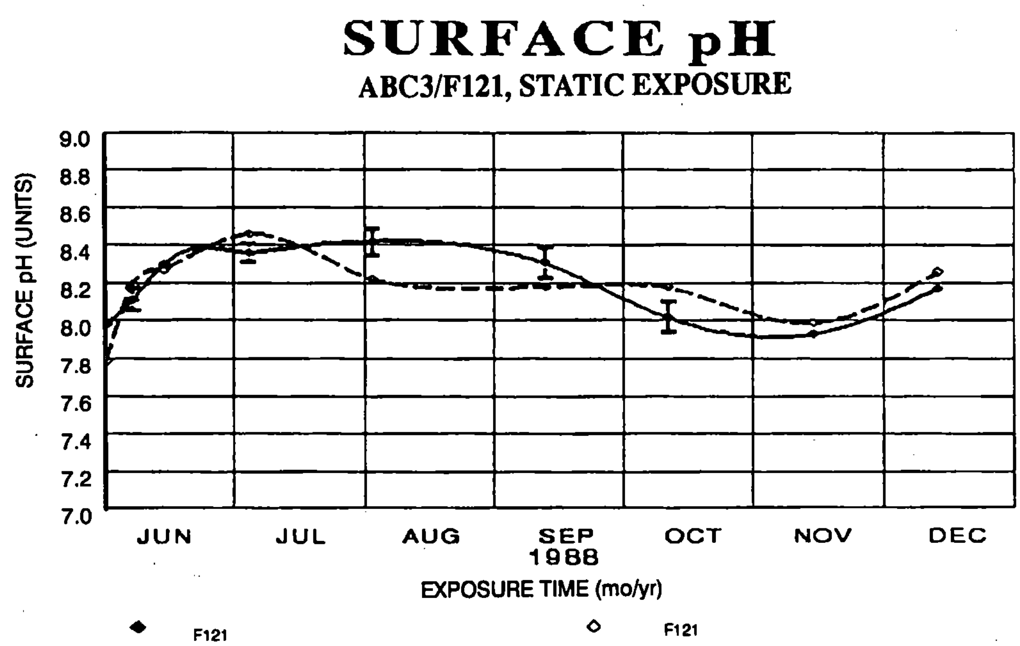
PAINT DETERIORATION

ABC3/F121, STATIC EXPOSURE



Graph B-21. Comparison of ABC3 and F121 fouling rate, leaching rate, and AF paint deterioration rate (PDR) in static exposure tests from July 1987 to July 1993.

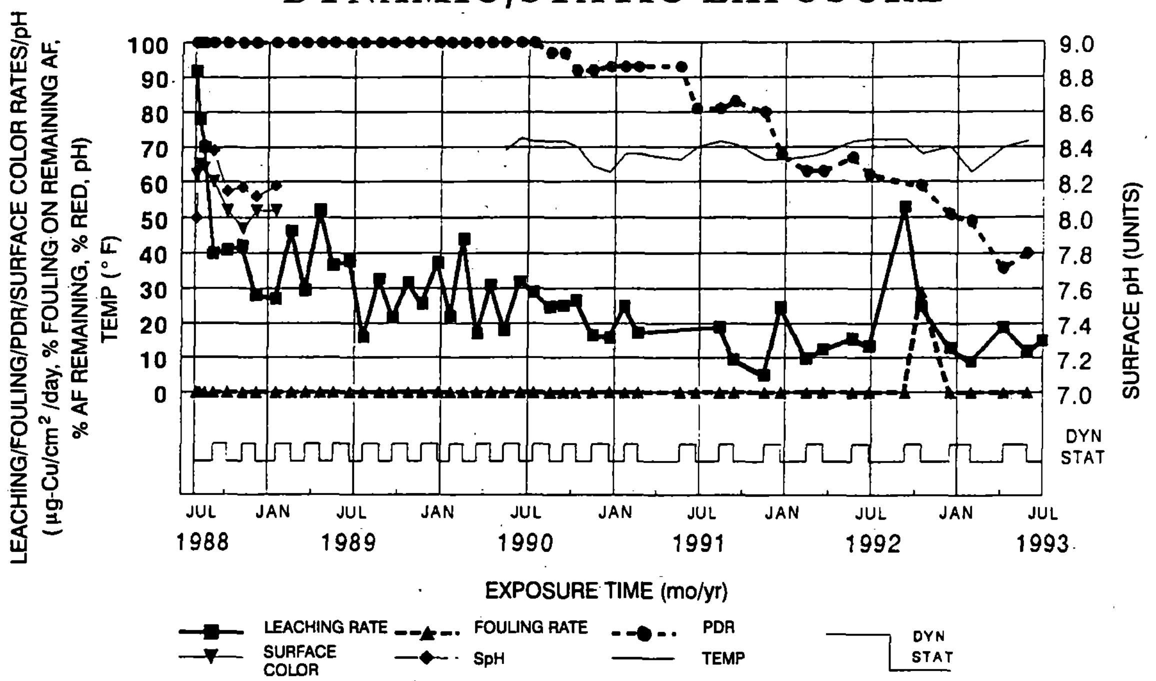




Graph B-22. Comparison of ABC3 and F121 surface color (% red) and surface pH in static exposure tests from June to December 1988.

BRA540

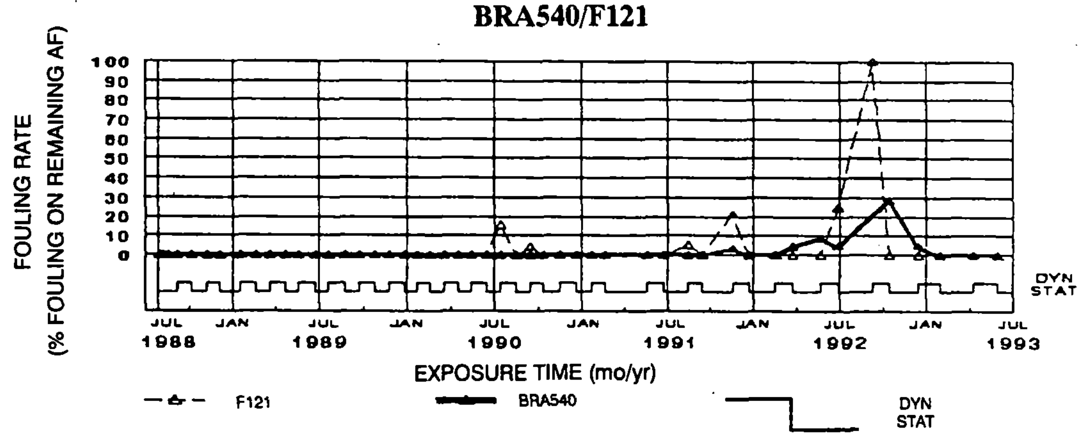
DYNAMIC/STATIC EXPOSURE



Graph B-23. Dynamic/static exposure tests for BRA540 from July 1988 to July 1993.

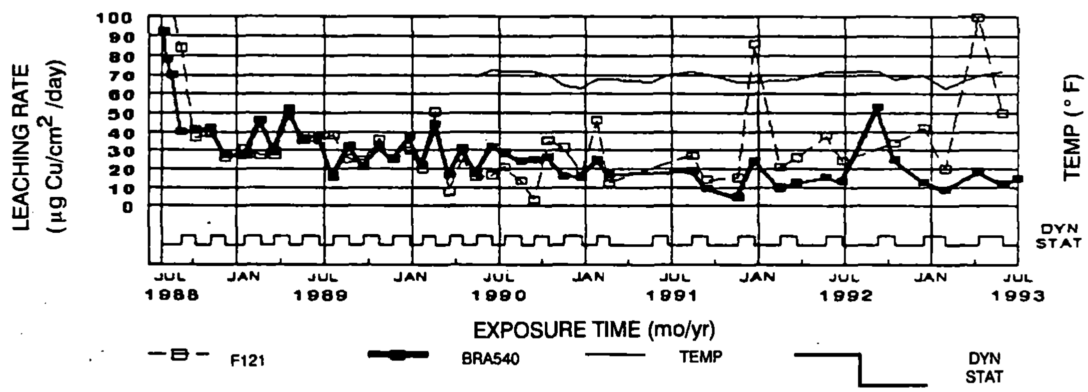
FOULING RATE

BRA540/F121



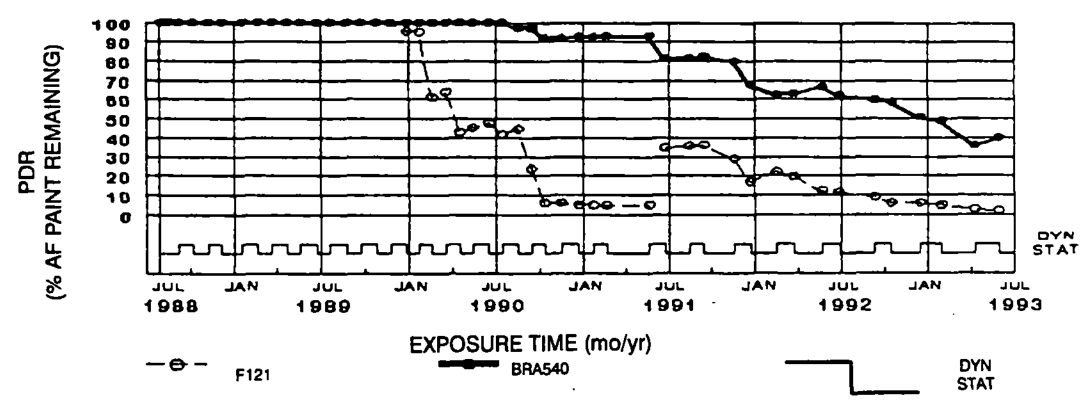
Cu LEACHING RATE

BRA540/F121



AF PAINT DETERIORATION RATE

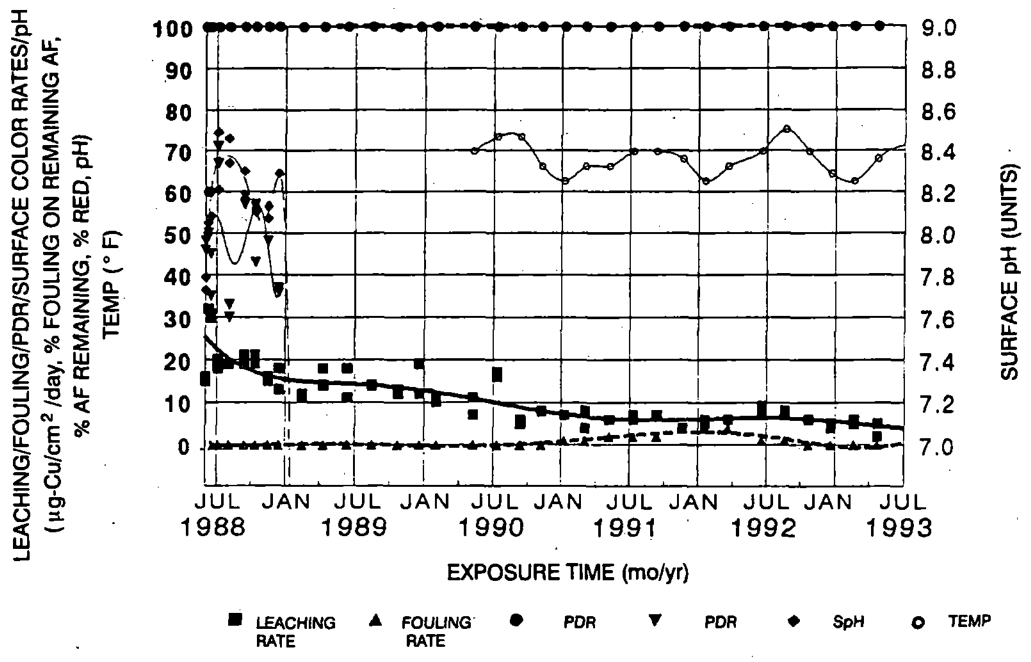
BRA540/F121



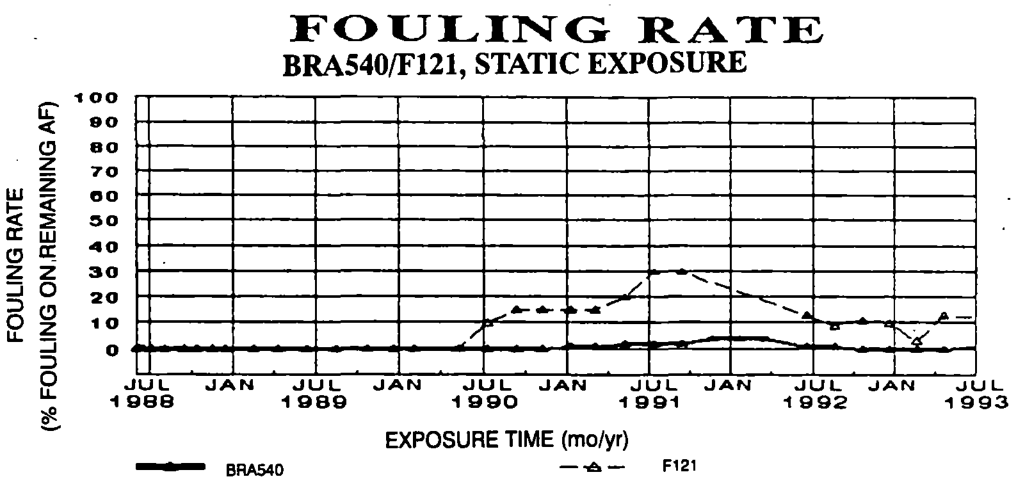
Graph B-24. Comparison of BRA540 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

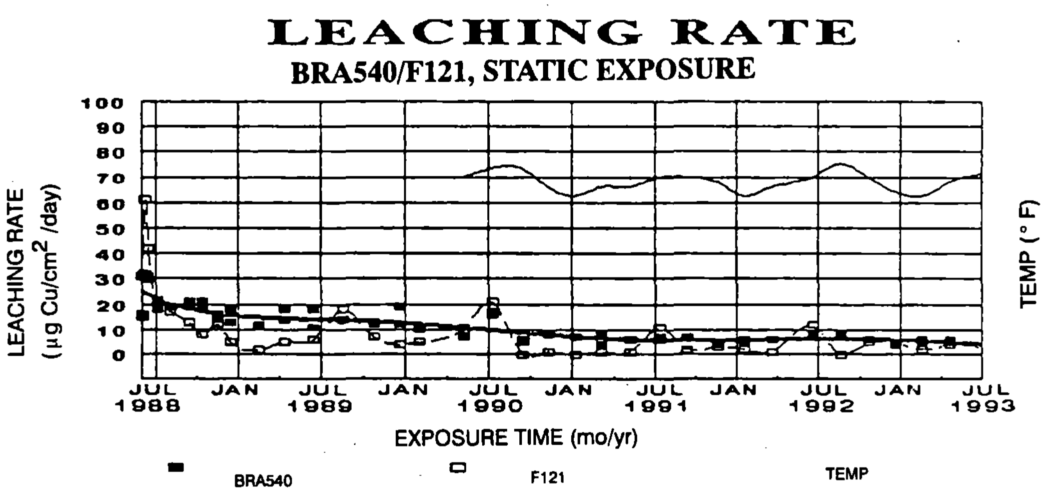
BRA540

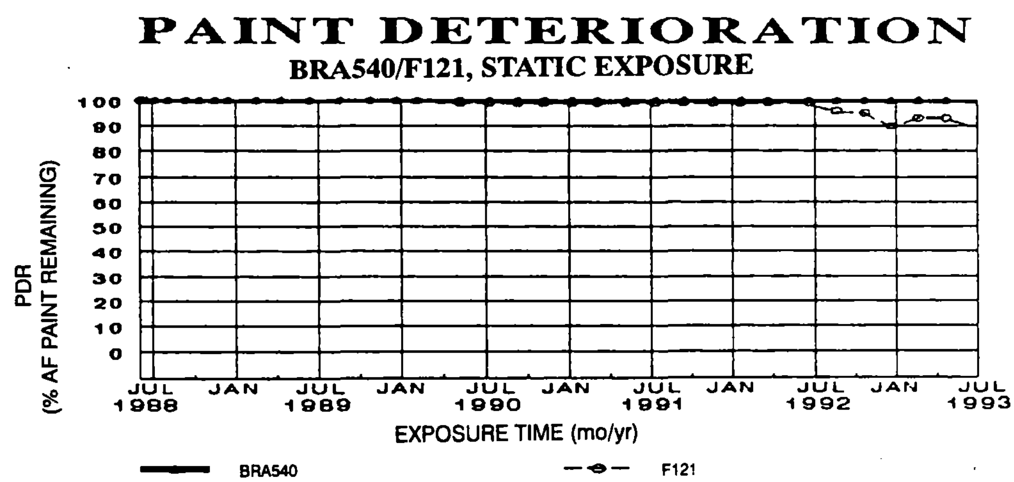
STATIC EXPOSURE



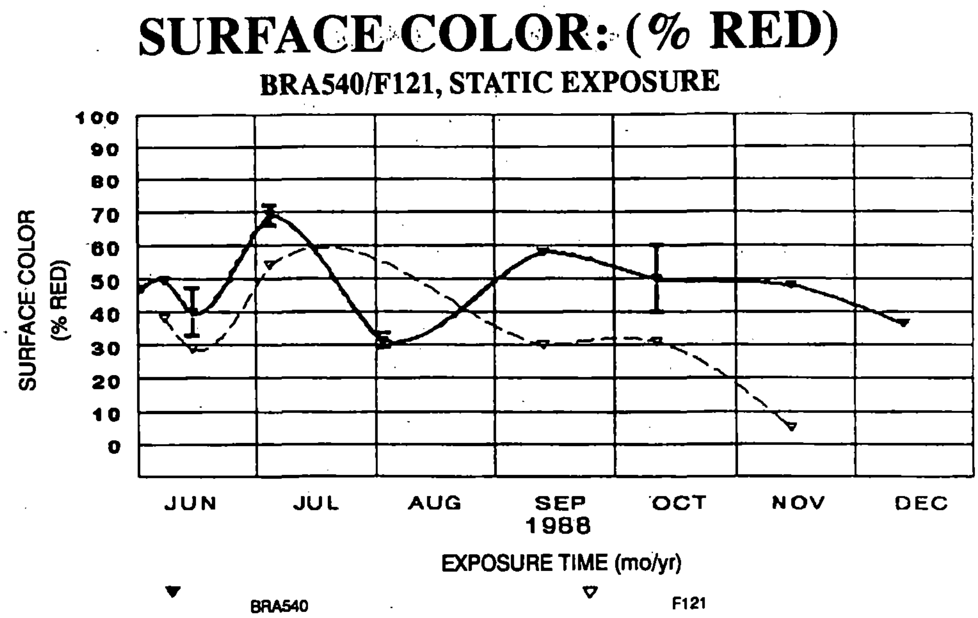
Graph B-25. Static exposure tests for BRA540 from July 1988 to July 1993.

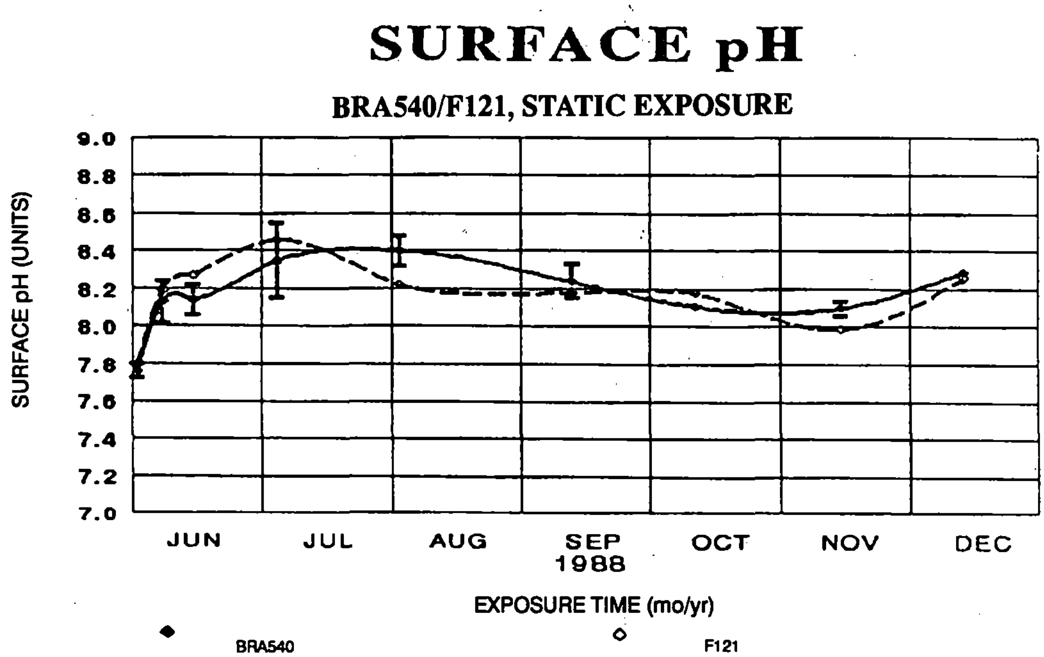






Graph B-26. Fouling rate, leaching rate, and AF paint deterioration rate (PDR) in static exposure tests for BRA540 and F121 from July 1988 to July 1993.

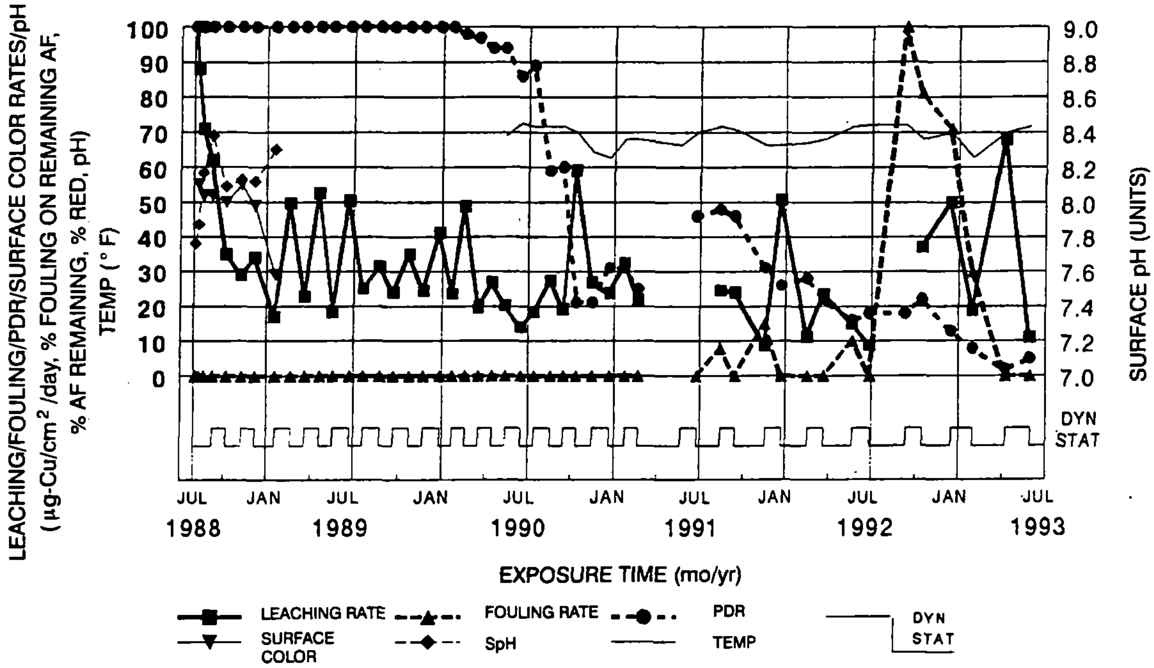




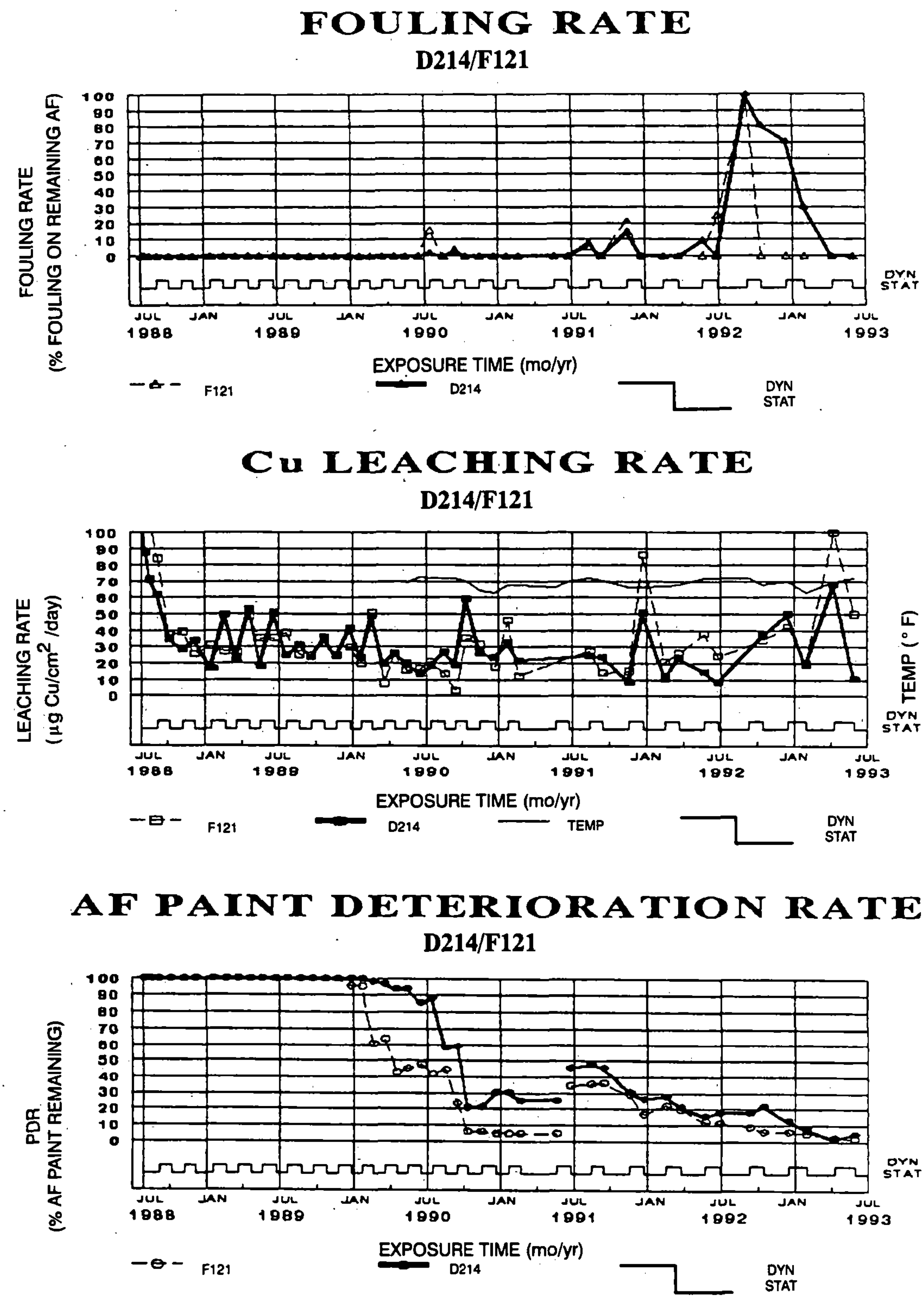
Graph B-27. Comparison of BRA540 and F121 surface (% red) color and surface pH in static exposure tests from June to December 1988.

D214

DYNAMIC/STATIC EXPOSURE



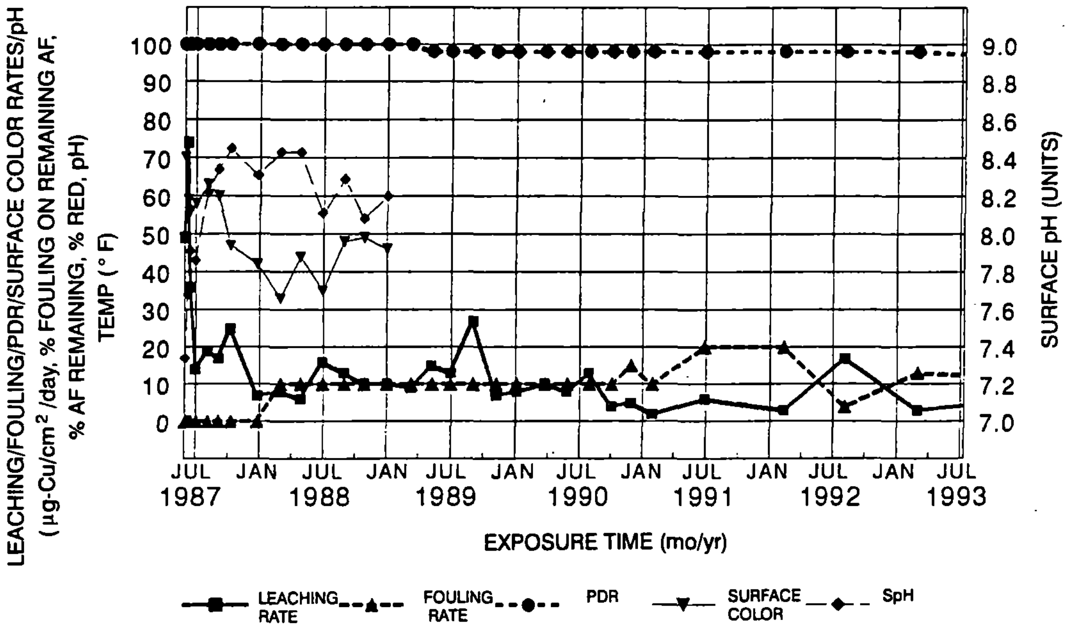
Graph B-28. Dynamic/static exposure tests for D214 from July 1988 to July 1993.



Graph B-29. Comparison of D214 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

D214

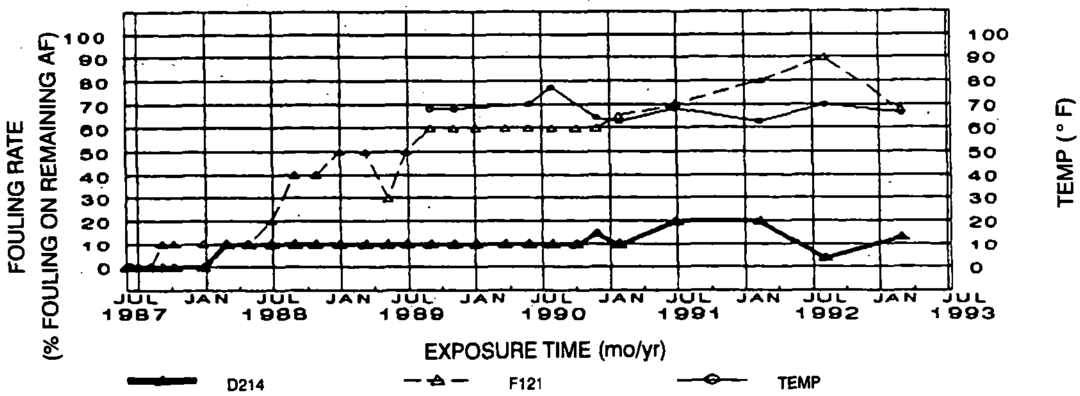
STATIC EXPOSURE



Graph B-30. Static exposure tests for D214 from July 1987 to July 1993.

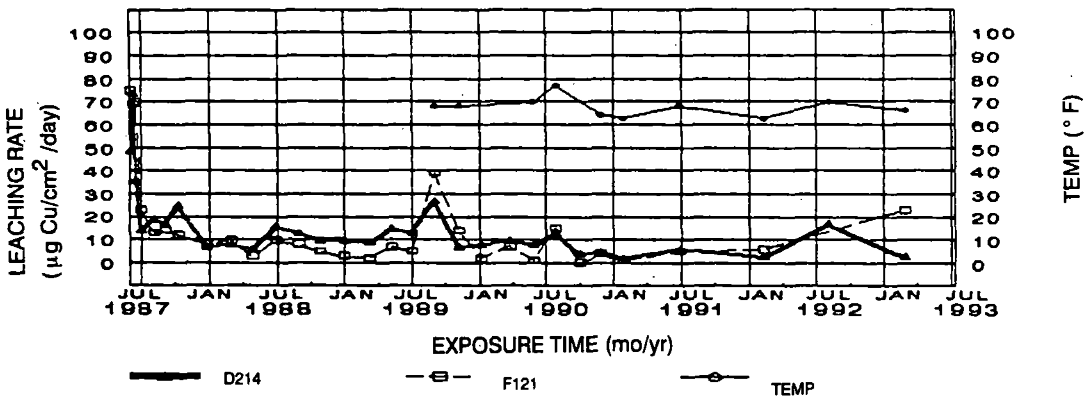
FOULING RATE

D214/F121, STATIC EXPOSURE



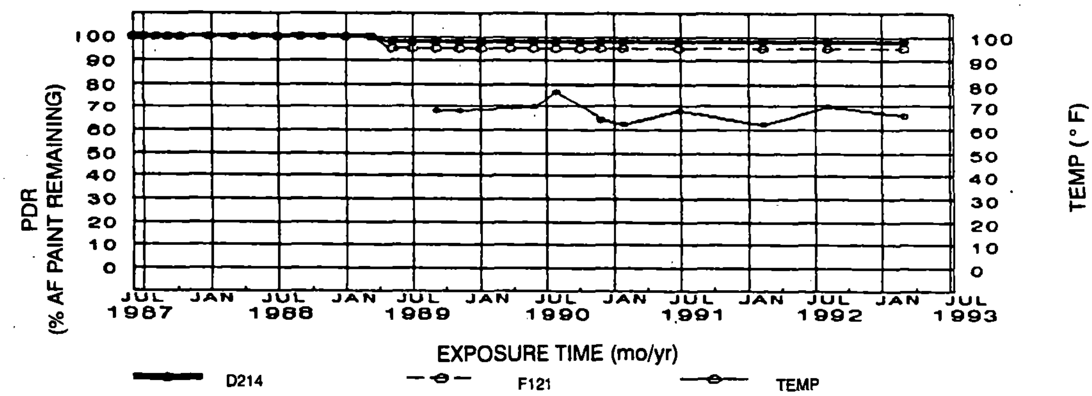
LEACHING RATE

D214/F121, STATIC EXPOSURE



PAINT DETERIORATION

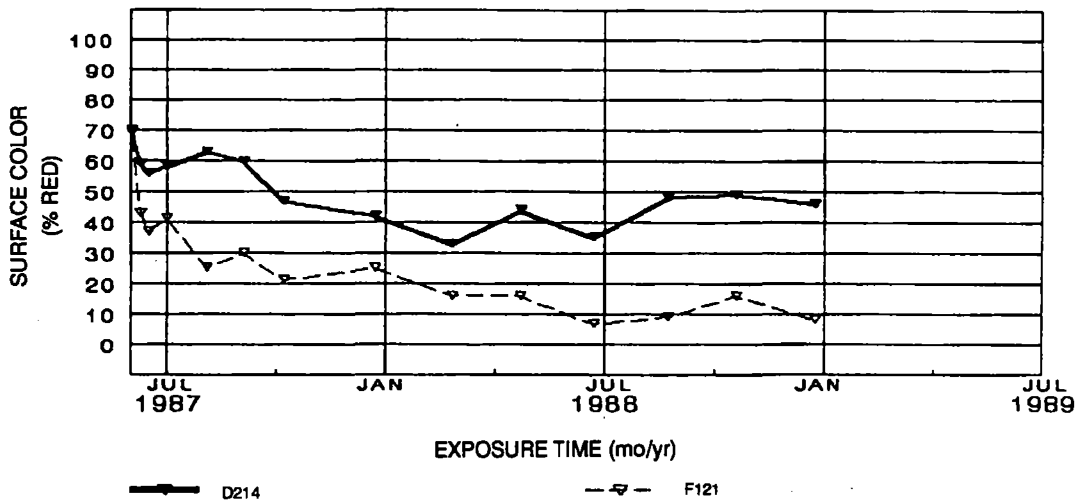
D214/F121, STATIC EXPOSURE



Graph B-31. Comparison of D214 and F121 fouling rate, leaching rate, and AF paint deterioration rates (PDR) in static exposure tests from July 1987 to July 1993.

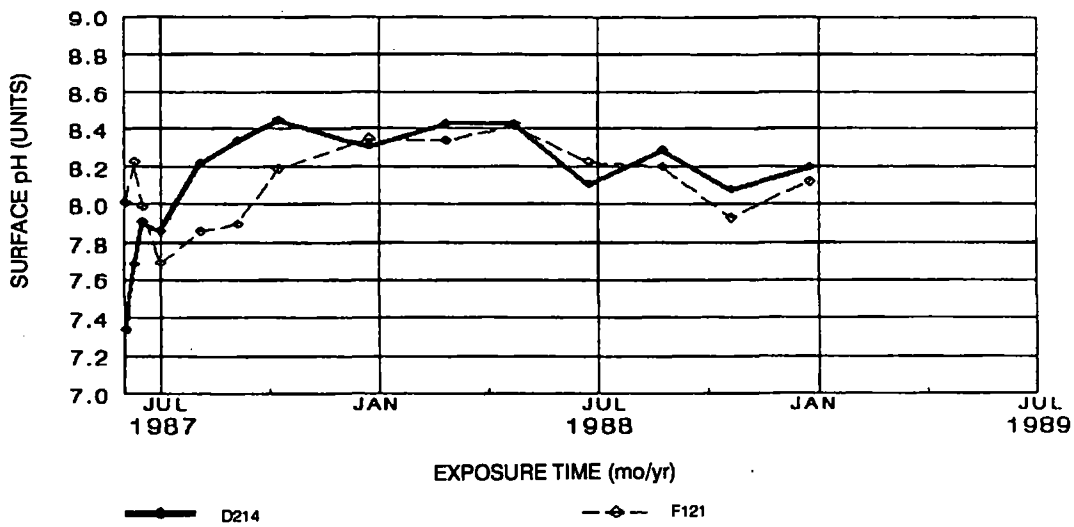
SURFACE COLOR: (% RED)

D214/F121, STATIC EXPOSURE



SURFACE pH

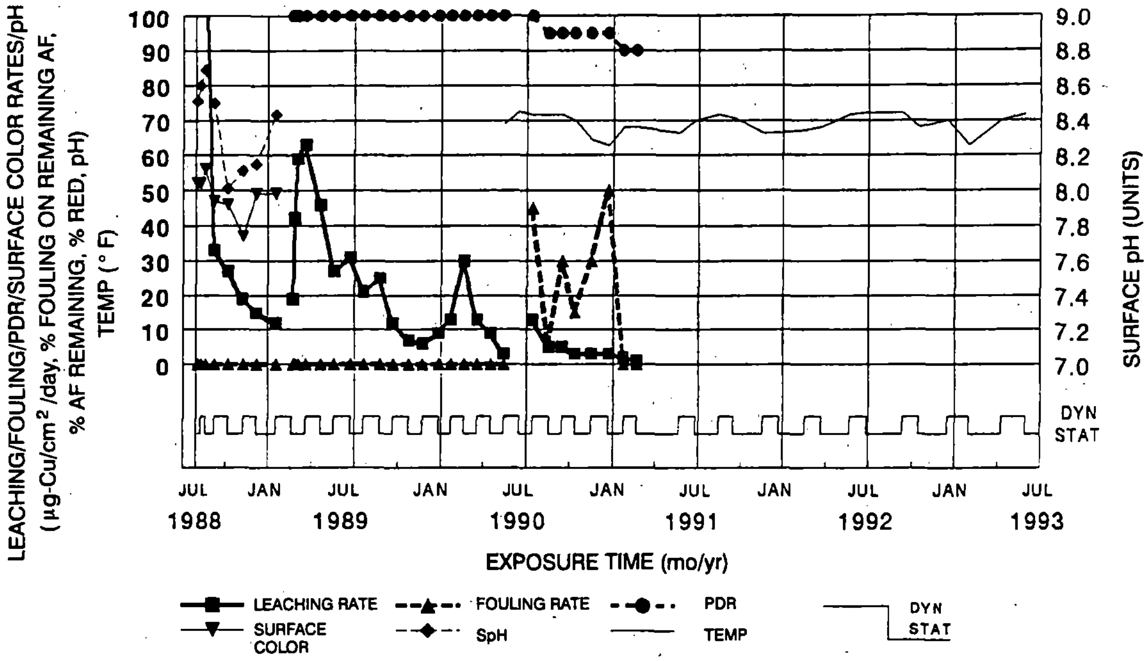
D214/F121, STATIC EXPOSURE



Graph B-32. Comparison of D214 and F121 surface color (% red) and surface pH in static exposure tests from July 1987 to July 1989.

AMERON 70

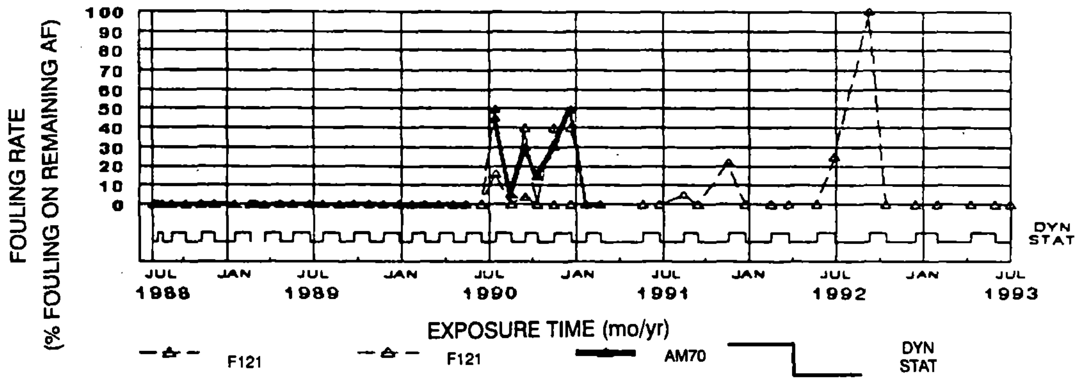
DYNAMIC/STATIC EXPOSURE



Graph B-33. Dynamic/static exposure tests for Ameron 70 from July 1988 to July 1993.

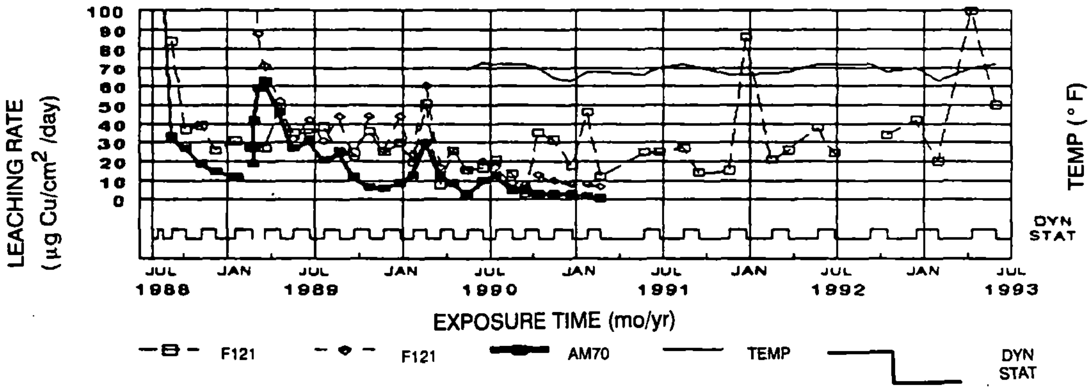
FOULING RATE

AM70/F121



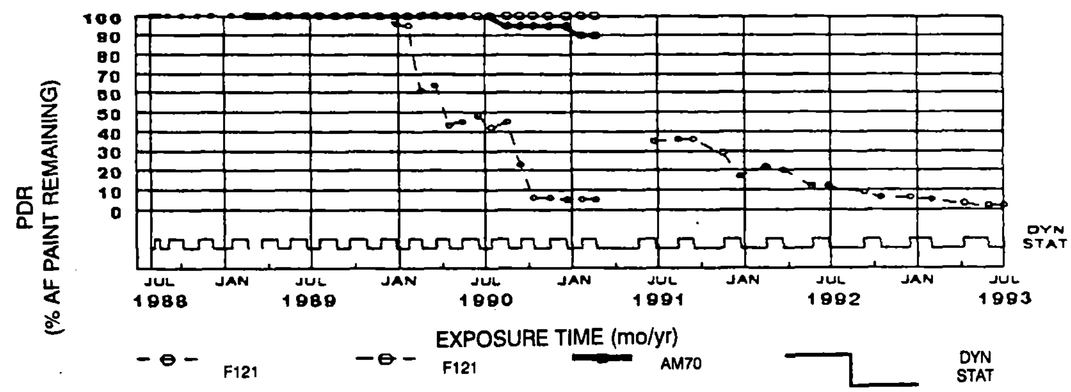
Cu LEACHING RATE

AM70/F121



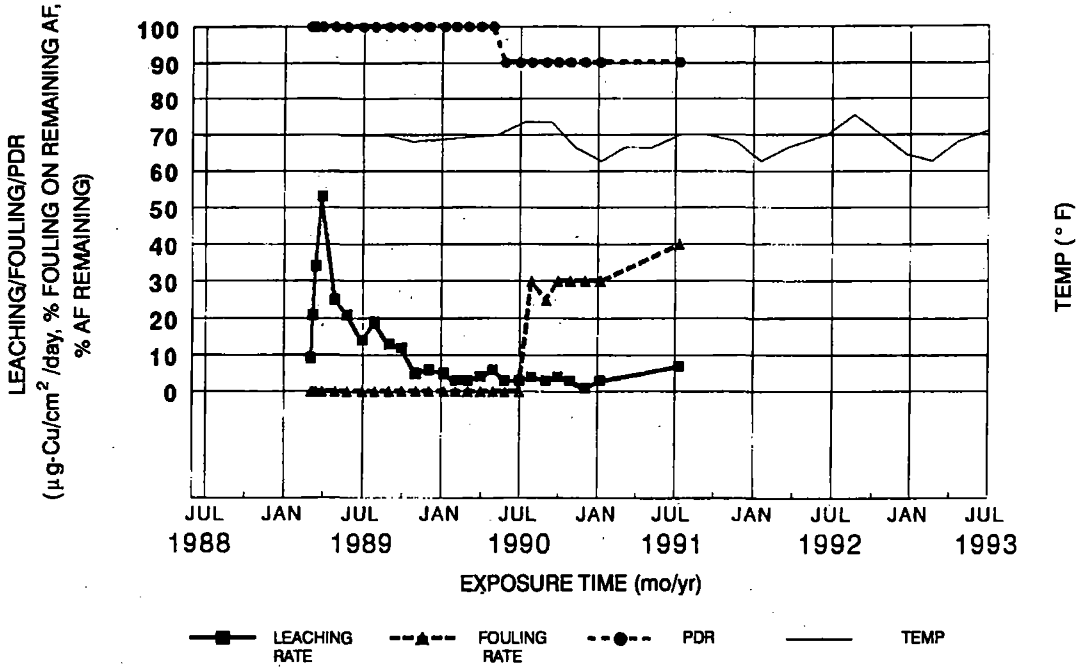
AF PAINT DETERIORATION RATE

AM70/F121



Graph B-34. Comparison of AM70 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

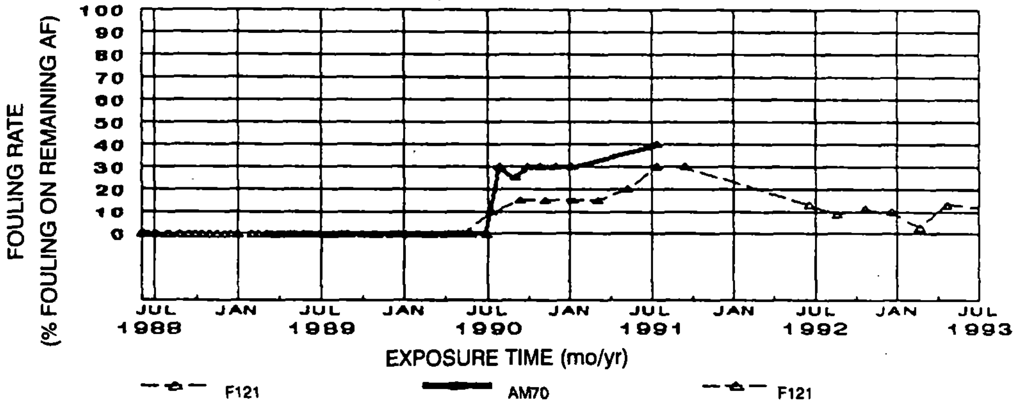
AMERON 70
STATIC EXPOSURE



Graph B-35. Static exposure tests for Ameron 70 from July 1988 to July 1993.

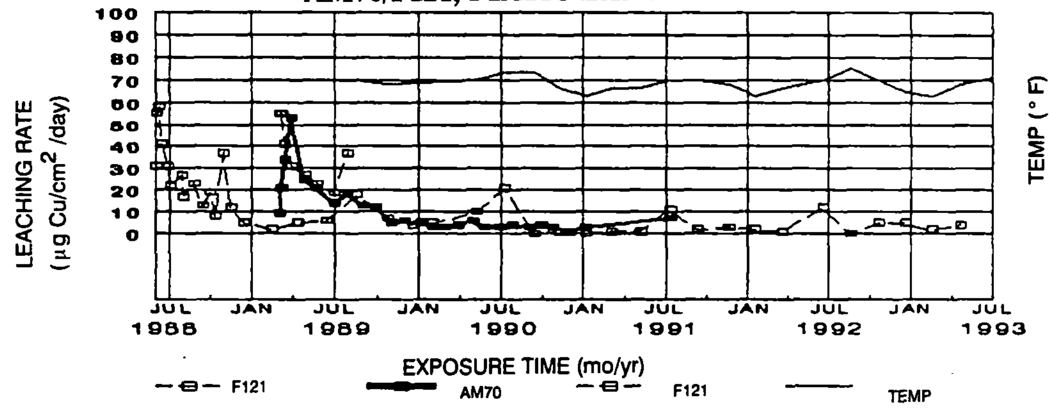
FOULING RATE

AM70/F121, STATIC EXPOSURE



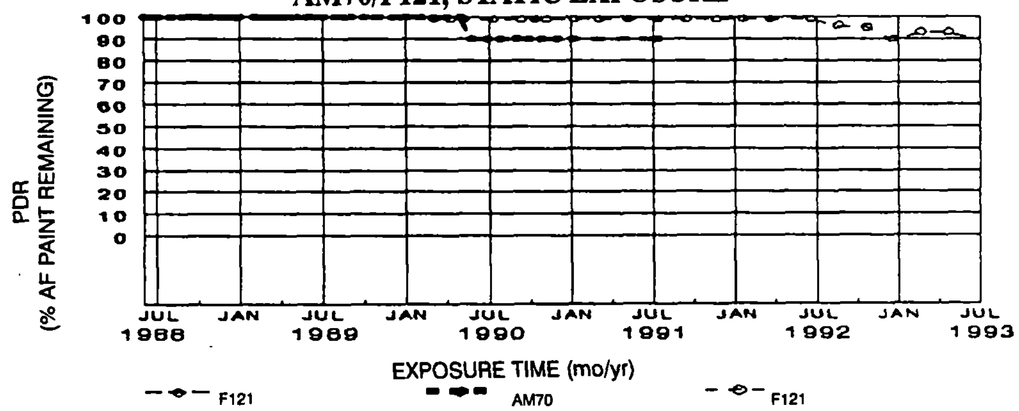
LEACHING RATE

AM70/F121, STATIC EXPOSURE



AF DETERIORATION RATE

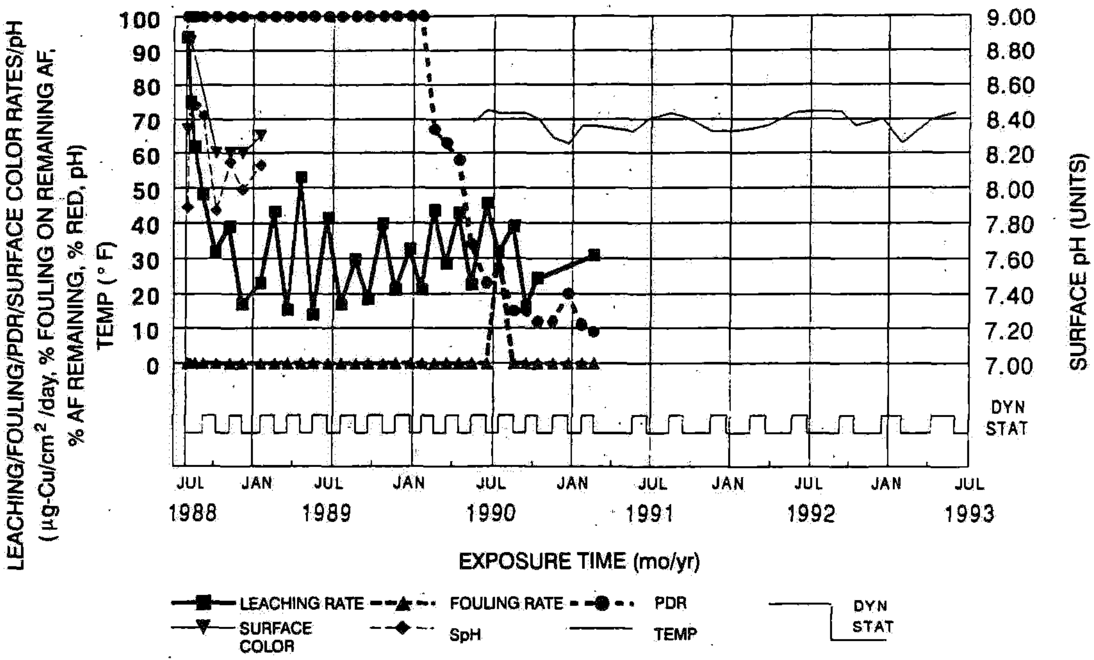
AM70/F121, STATIC EXPOSURE



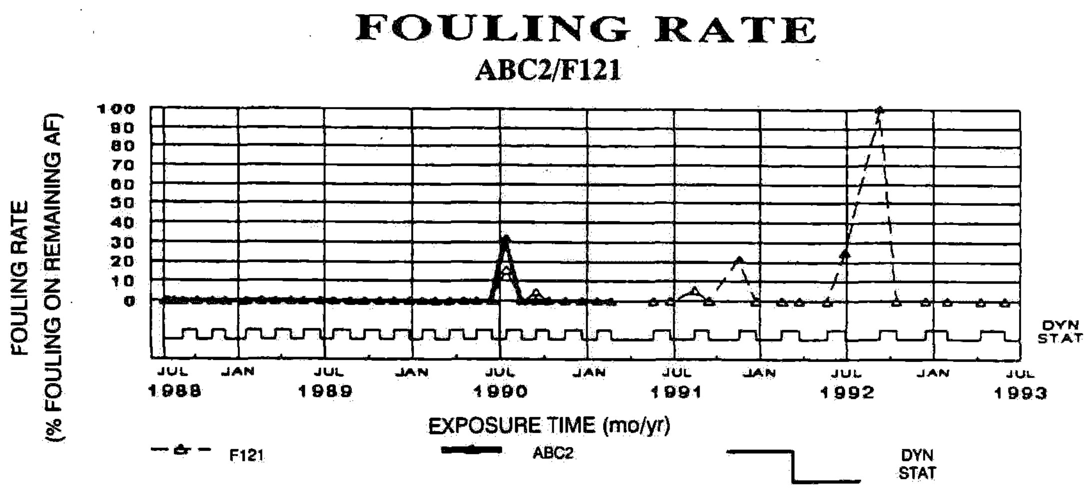
Graph B-36. Comparison of AM70 and F121 fouling rate, leaching rate, and AF paint deterioration rate (PDR) in static tests from July 1988 to July 1993.

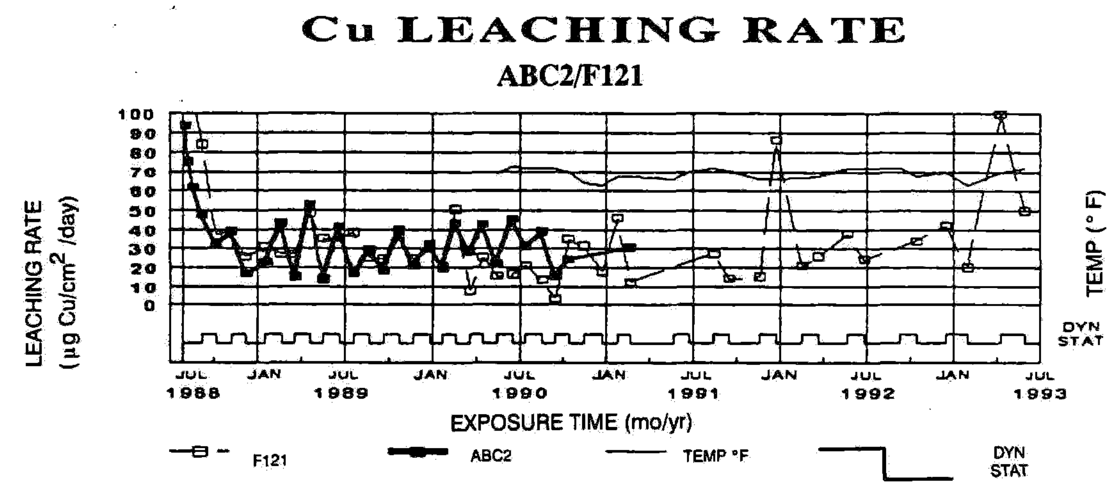
DEVOE ABC2

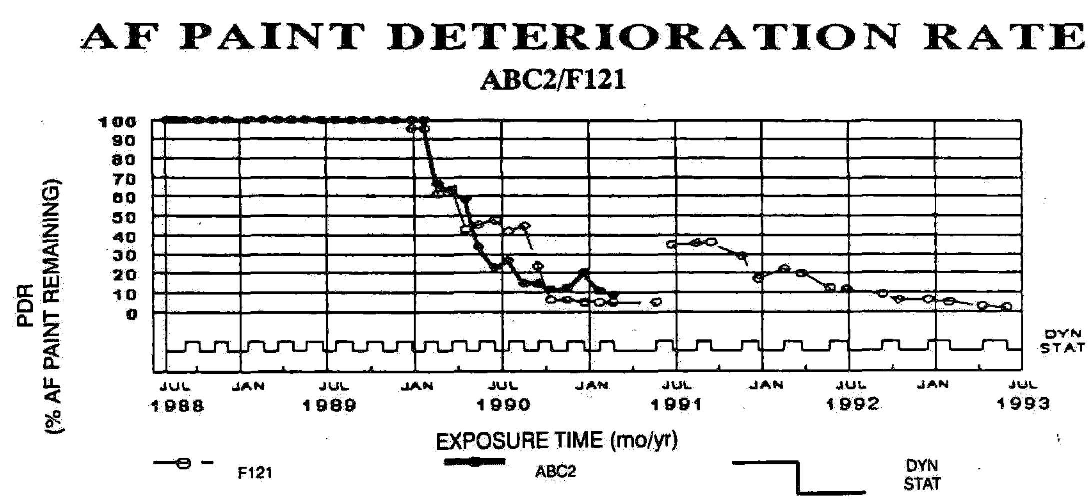
DYNAMIC/STATIC EXPOSURE



Graph B-37. Dynamic/static exposure tests for Devoe ABC2 from July 1988 to July 1993.



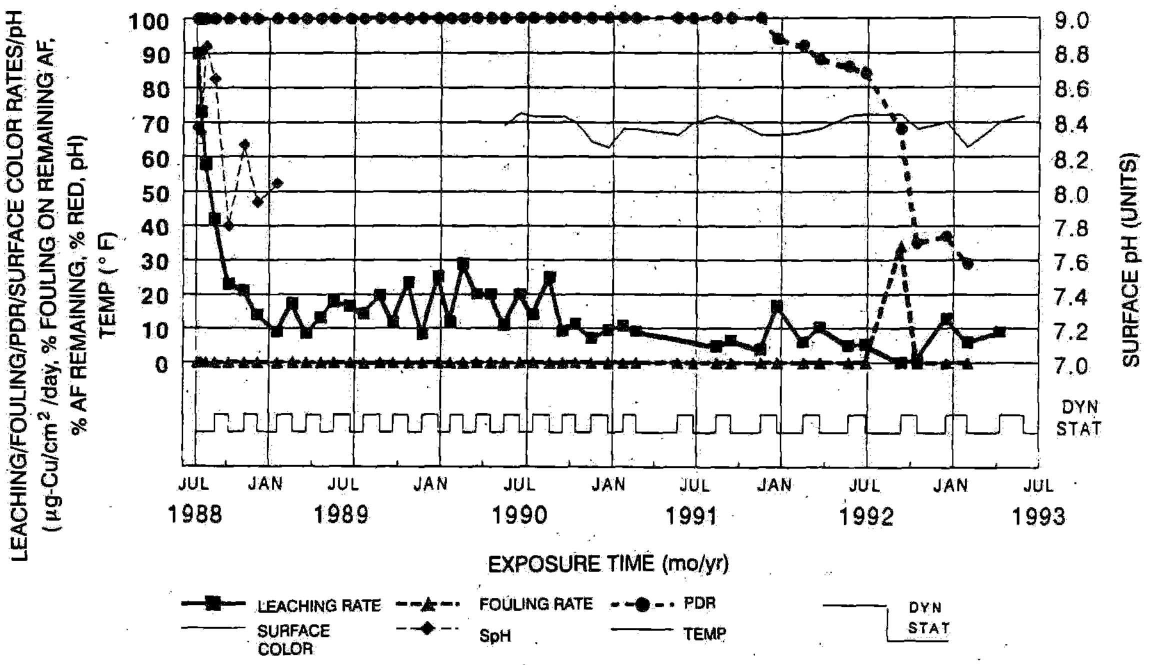




Graph B-38. Comparison of Devoe ABC2 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rates (PDR) in dynamic/static tests from July 1988 to July 1993.

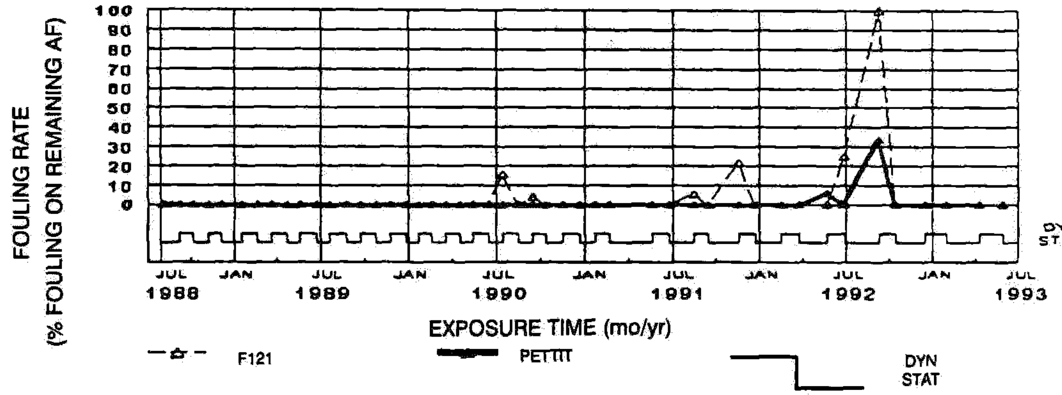
PETTIT

DYNAMIC/STATIC EXPOSURE

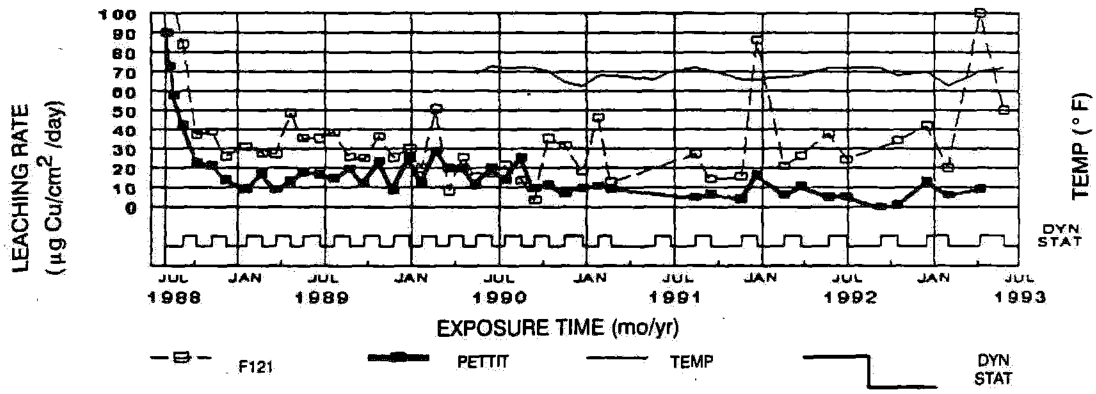


Graph B-39. Dynamic/static exposure tests for PETTIT from July 1988 to July 1993.

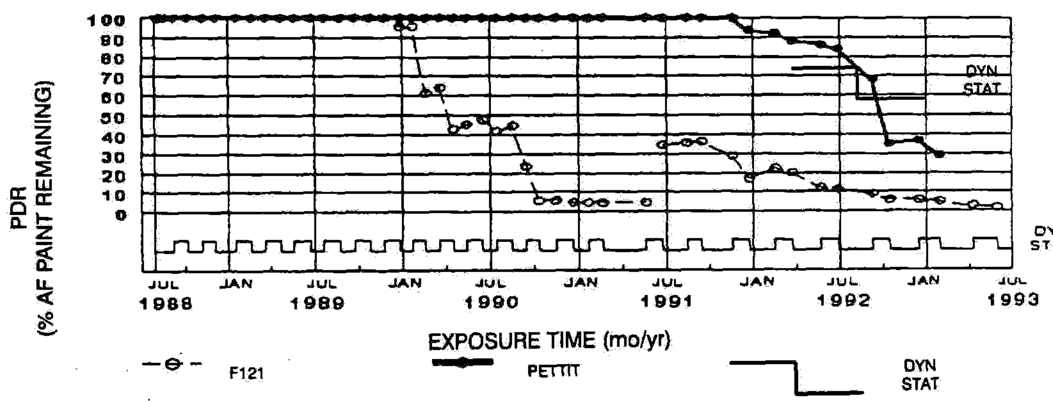
FOULING RATE
PETTIT/F121



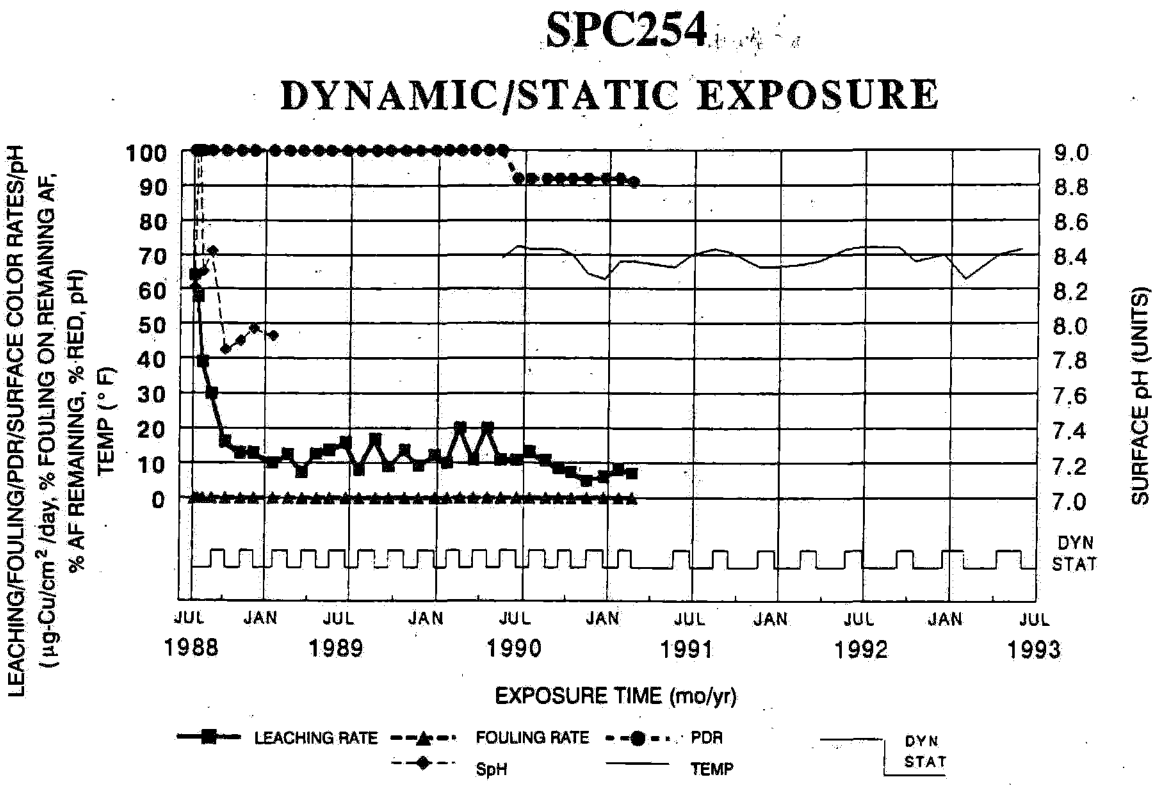
Cu LEACHING RATE
PETTIT/F121



AF PAINT DETERIORATION RATE
PETTIT/F121



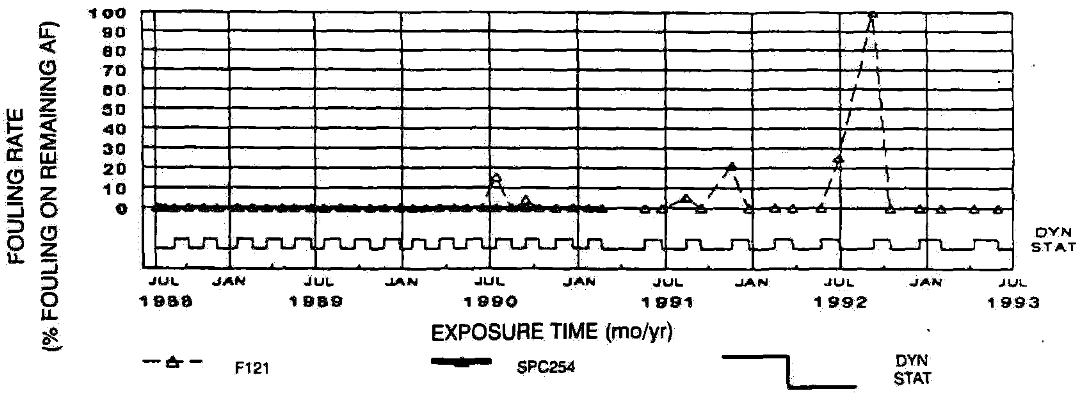
Graph B-40. Comparison of PETTIT and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.



Graph B-41. Dynamic/static exposure tests for SPC254 from July 1988 to July 1993.

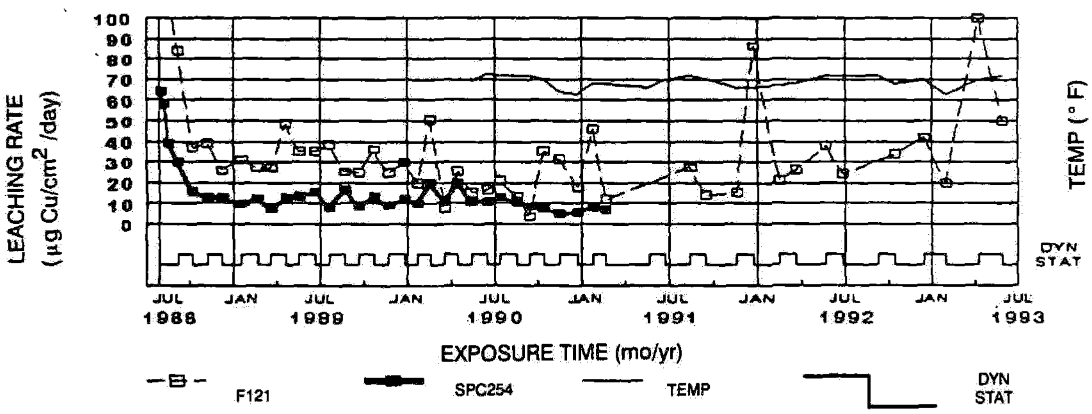
FOULING RATE

SPC254/F121



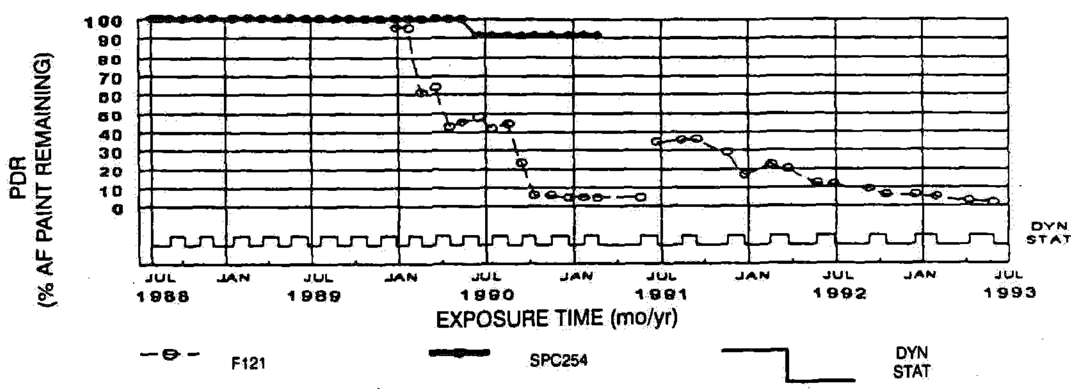
Cu LEACHING RATE

SPC254/F121



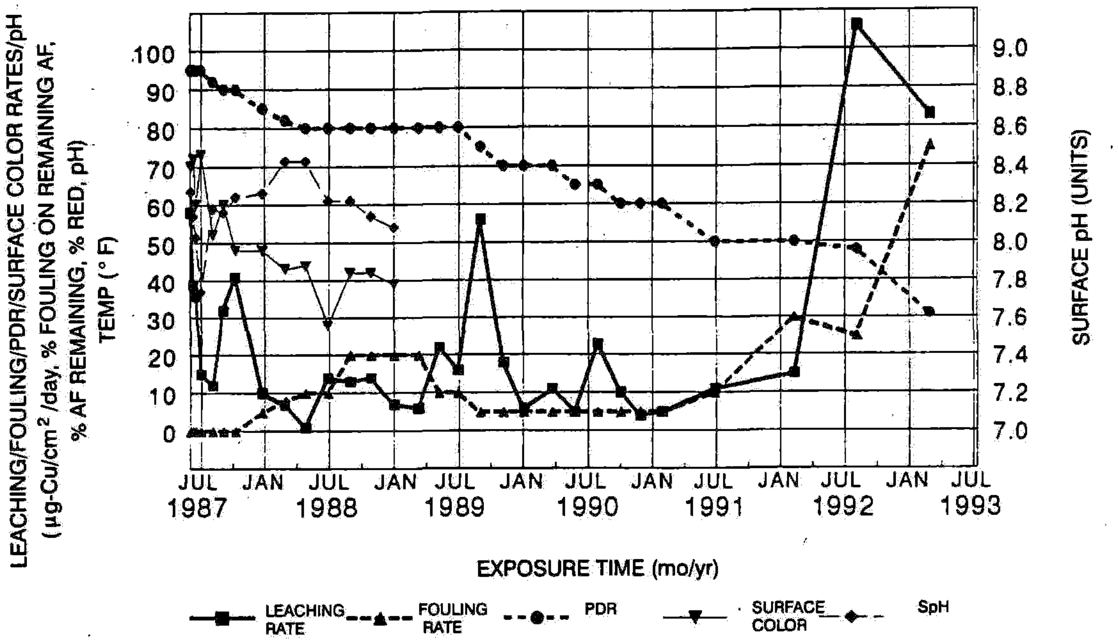
AF PAINT DETERIORATION RATE

SPC254/F121



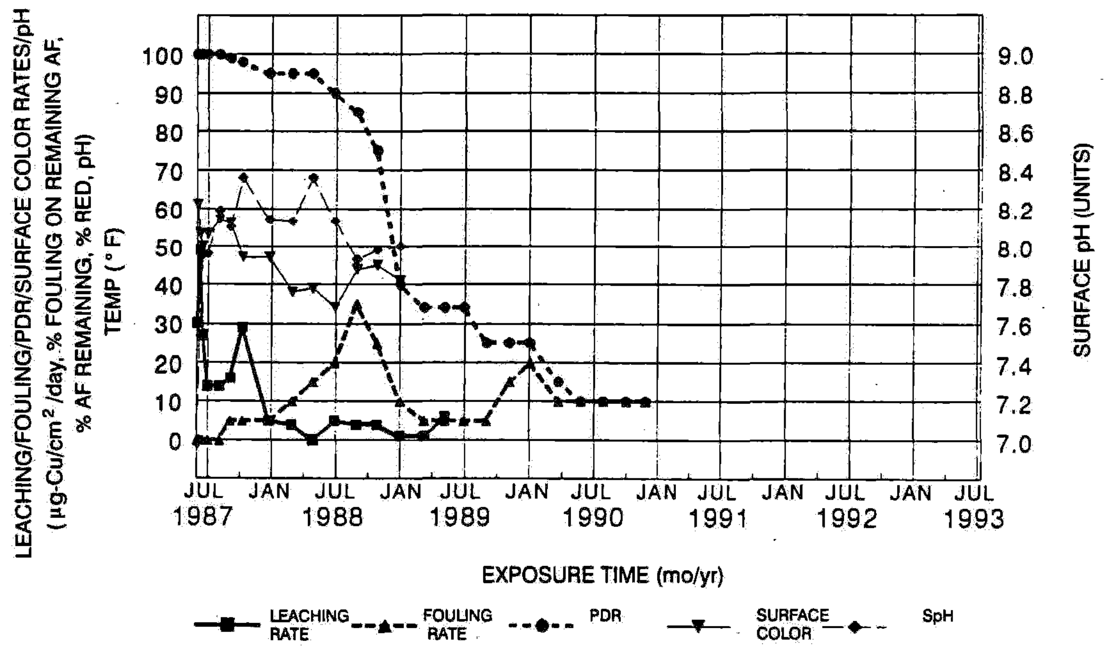
Graph B-42. Comparison of SPC254 and F121 fouling rate, Cu leaching rate, and AF paint deterioration rate (PDR) in dynamic/static tests from July 1988 to July 1993.

FARBOIL C.R. 83023-15
STATIC EXPOSURE



Graph B-43. Static exposure tests for Farboil C. R. 83023-15 from July 1987 to July 1993.

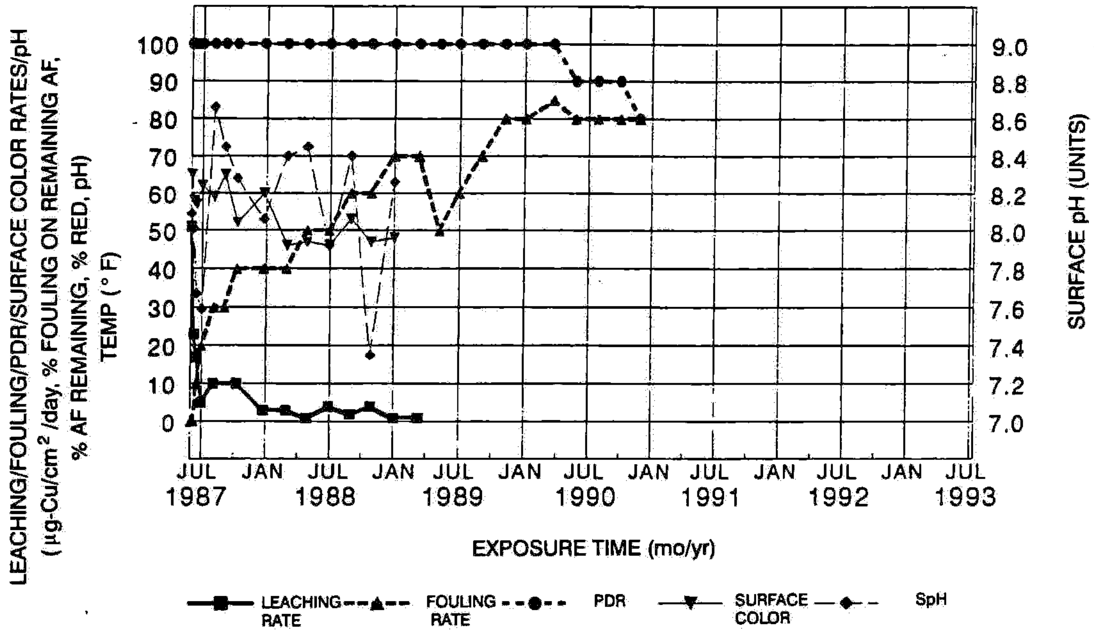
FARBOIL SUPER TROPICAL 1260
STATIC EXPOSURE



Graph B-44. Static exposure tests for Farboil super tropical 1260 from July 1987 to July 1993.

FARBOIL-844015-1

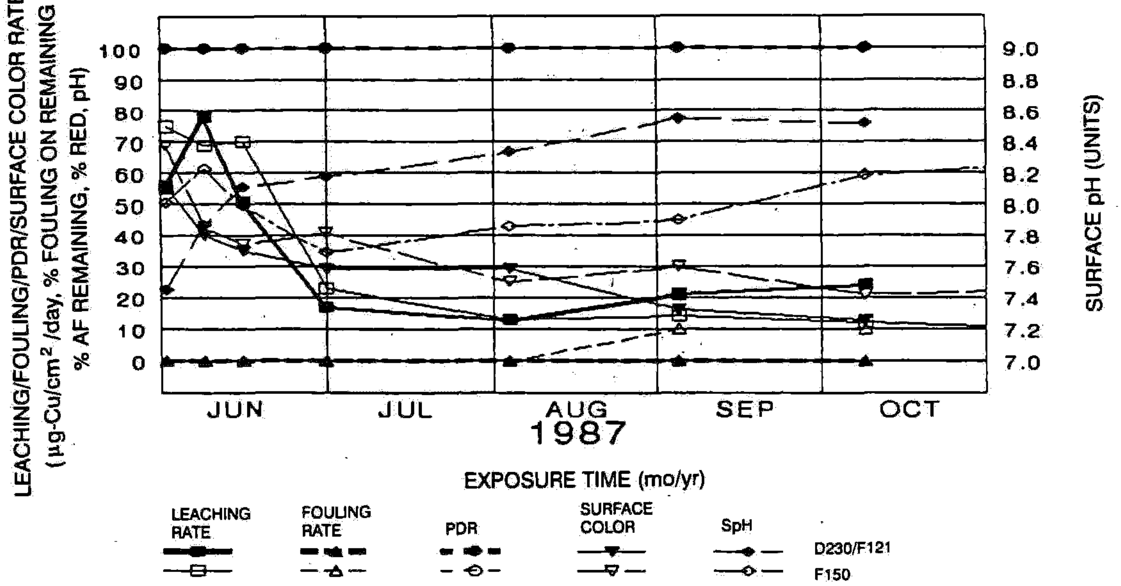
STATIC EXPOSURE



Graph B-45. Static exposure tests for Farboil 844015-1 from July 1987 to July 1993.

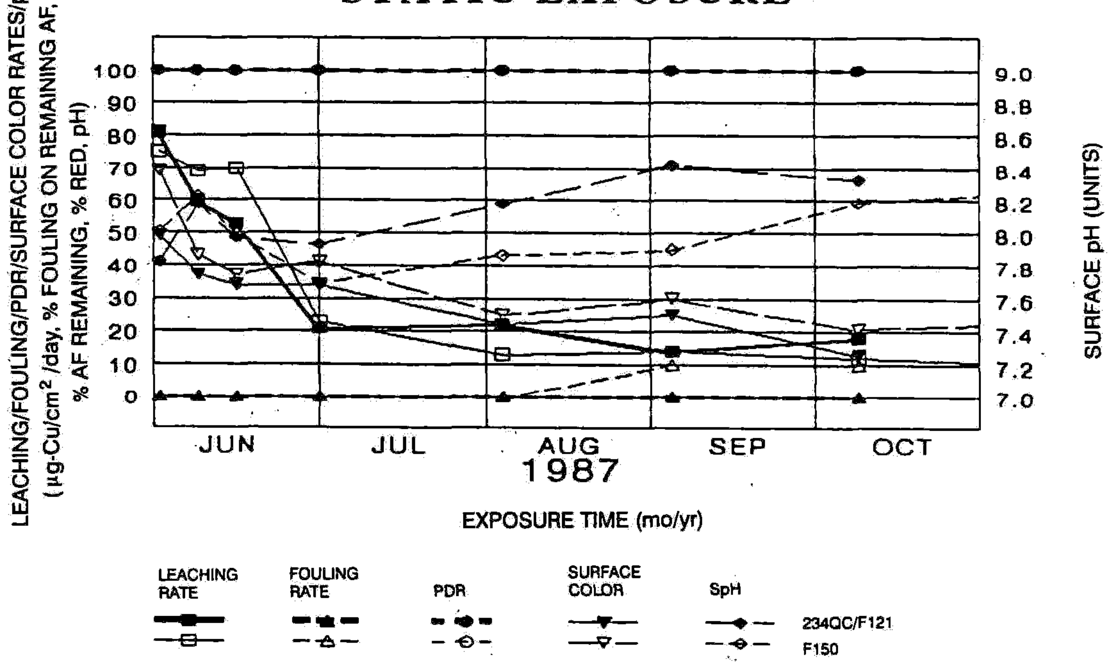
F121 on DEVOE 230

STATIC EXPOSURE



F121 on DEVOE 230

STATIC EXPOSURE



Graph B-46. Comparison of F121 on Devoe 230 and F121 on Devoe 234QC with F121 on F150 in static exposure tests from June to October 1987.

REPORT DOCUMENTATION PAGE

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6. AUTHOR(S)

E. Lindner

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC),
RDT&E Division
San Diego, CA 92152–5001

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13. ABSTRACT *(Maximum 200 words)*

Nine commercial and experimental paint systems were tested and evaluated for the five years between August 1988 and July 1993 in a dynamic/static cycle test. The F–121 Navy standard paint, a non-ablative coating, served as control. Two other non-ablative coatings were included: M–121, a modified F–121 formula, and Devoe F–214. Devoe ABC–3, a non-organotin version of Devoe ABC–2 and International BRA–540 were ablative Cu_2O coatings. Ameron F–70 was also an ablative copper coating using copper flakes instead of the customary copper salts as biocide. Three paint systems: International SPC–245, Devoe ABC–2, and PETTIT contained organotin and Cu_2O as biocides and served as additional reference paints for evaluation.

In the dynamic/static cycling exposure test all AF coatings were effective in resisting biofouling throughout the length of their exposure. The paint systems ultimately failed either because the paint integrity was weakened by blistering, peeling and flaking, or because the AF coating was removed by erosion under the high currents.

BRA–540 performed best among the copper-based coatings; it had an effective lifetime of over four years, that equals the performance of PETTIT and SPC–245 organotin-based paint systems. Devoe F–214 performed significantly better than the standard Navy F–121 coating and proved to be effective for six years in the static exposure test. The ABC system appeared to be too soft, by ablating much faster than F–121 or BRA–540. Also, BRA–540 performed better than ABC–3 and F–121 in the static exposure test. Ameron F–70 had very poor paint integrity and caused severe galvanic corrosion where the bare steel was exposed by damage. Ameron F–70 failed in both the static and in the dynamic/static exposure tests.

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